technische universität dortmund

Bundesministerium für Bildung und Forschung

LHCb

Lepton flavour universality tests at LHCb

57th Recontres de Moriond 2023 - QCD and high energy interactions

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On behalf of the LHCb Collaboration

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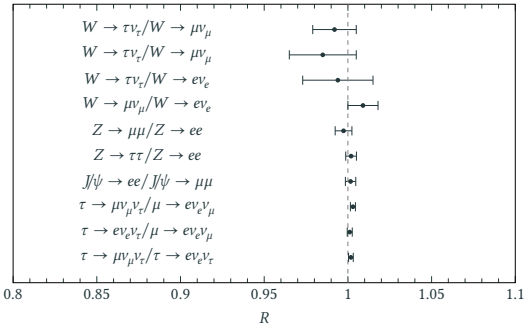
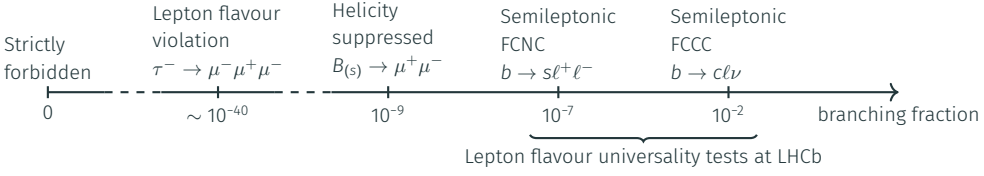
Introduction

Introduction

- Lepton flavour universality (LFU) in the SM: electroweak couplings are independent of lepton flavours
- Verified on tree-level with EM interactions, Z and light quark decays
- New physics particles could lead to a violation of LFU
- At LHCb: Tests of LFU with semileptonic $b \to c\ell\nu$ and rare $b \to s\ell^+\ell^-$ decays in the heavy quark sector

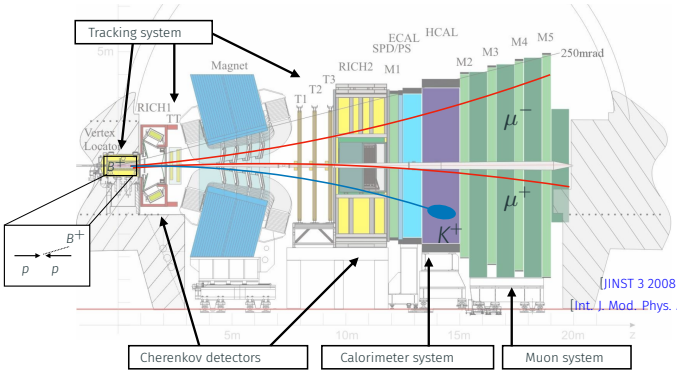




Lepton Flavour Universality at the LHCb detector

LHCb detector (Run 1 and 2)

- Precise b hadron identification through displaced vertex reconstruction
  $\sigma_{\text{IP}} = 15 \pm 29 p_T/\text{mm}$
- Low transverse momentum triggers
- Precise tracking detectors with dipole magnet
  $\sigma_p/p \sim 0.5\,\%$
- PID system: calorimeters, muon system, cherenkov detectors



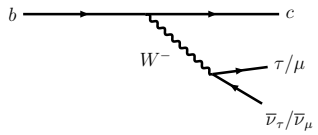
[JINST 3 2008 S08005]
[Int. J. Mod. Phys. A 30 2015 1530022]

- e: emit bremsstrahlung, high occupancy in ECAL, lower reconstruction efficiency
- μ: negligible bremsstrahlung, low occupancy, high reco. efficiency
- τ: challenging to reconstruct because of neutrinos

Lepton flavour universality tests with $b \to c\ell\nu$ decays

LFU with $b \to c\ell\nu$ overview

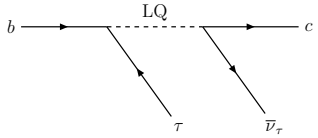
- Allowed charged tree-level current with large decay rates
- **LHCb: study ratios R_{H_c} with τ and μ**



$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau \nu_\tau)}{\mathcal{B}(H_b \to H_c \mu \nu_\mu)}$$

with $H_b = B^0, B^+, \Lambda_b, \ldots$
and $H_c = D^{*,+}, D^0, D^+, \Lambda_c, J/\psi, \ldots$

- **Advantages:** remove dependency on $|V_{cb}|$, reduction of experimental and theoretical uncertainties
- Possible sensitivity of R_{H_c} to BSM couplings of third lepton generation with, e.g., leptoquarks, charged Higgs, W'



- $H_b \to H_c \tau \nu_\tau$ can further decay with
  - "Hadronic": $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
  - "Muonic": $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$
- Long standing deviation from SM prediction of R_{D^0} and R_{D^*} at 3σ level [e.g. Eur. Phys. J. C77 (2017) 895]

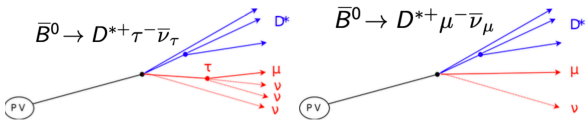
Simultaneous measurement of R_{D^*} and R_{D^0} [arXiv:2302.02886 (submitted to PRL)]

- **New:** First simultaneous measurement of

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$

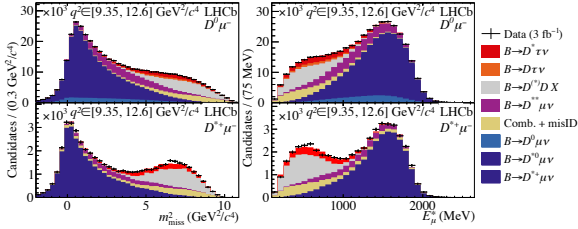
with $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ and $D^* \to \bar{D}(\to \pi K)\pi$

- Using LHCb Run 1 data
- Before: $R(D^*)$ with Run 1 $D^{*+}\mu^-$ data with 2.1σ deviation from SM prediction [PRL 115, 111803]
- **Now:** higher branching fractions and efficiency using $D^0\mu^-$ sample $5\times$ bigger than $D^{*+}\mu^-$



[CERN seminar talk]

- Reconstruction challenges:
  - 3 neutrinos: spread out peaks in any distribution
  - Backgrounds: $B \to D^{**}$, $B \to DDX$, mis-ID, combinatorial
  - Select muonic τ decays only
- Select $D^0\mu^+$ or $D^*\mu^+$
- Template fit with $m^2_{miss} = (p_B - p_{D(*)} - p_\mu)^2$, $q^2 = (p_B - p_{D(*)})^2$ and E^*_μ:



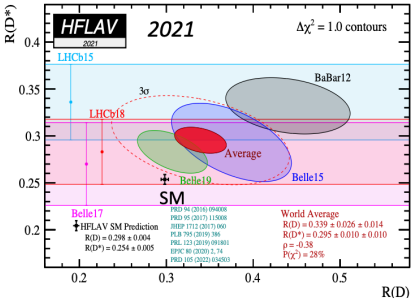
[arXiv:2302.02886]

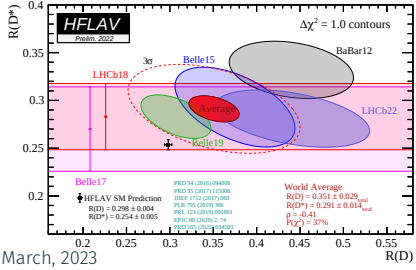
Simultaneous measurement of R_{D^*} and R_{D^0} [arXiv:2302.02886 (submitted to PRL)]

Result

- $R_{D^*} = 0.281 \pm 0.018 \pm 0.024$
- $R_{D^0} = 0.441 \pm 0.060 \pm 0.066$
- Correlation $\rho = -0.43$
- 1.9σ agreement with SM

- Largest systematic uncertainty due to limited data and simulation samples
- New preliminary average: slightly lower R_{D^*}, slightly higher R_{D^0}
- $3.3\sigma \rightarrow 3.5\sigma$ agreement with SM





R_{D^*} with hadronic τ decays [LHCb-PAPER-2022-052 (In preparation), CERN seminar talk]

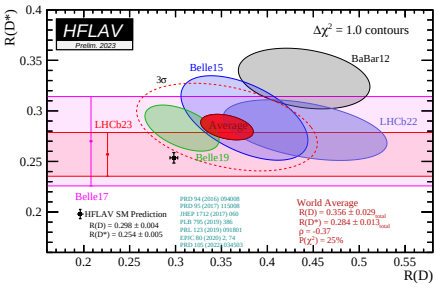
- **Last week:** R_{D^*} with $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\tau$
- Adding 2015 + 2016 data to LHCb Run 1 analysis [PRL 120 171802 (2018),PRD 97 072013 (2018)]
- Normalisation mode with same **visible** three-prong final state : $B^0 \to D^{*-}3\pi^\pm$

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = \frac{N_{\text{Sig.}}}{N_{\text{Norm.}}} \cdot \frac{\epsilon_{\text{Norm.}}}{\epsilon_{\text{Sig.}}} \cdot \frac{1}{\mathcal{B}(\tau^+ \to 3\pi^\pm(\pi^0)\overline{\nu}_\tau)}$$

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

- 3D template fit with $q^2 \equiv (p_{B^0} - p_{D^*})^2$, τ^+ decay time, τ vs. D_s^+ BDT output

- Result: $R_{D^*} = 0.257 \pm 0.012(\text{stat.}) \pm 0.014(\text{syst.}) \pm 0.012(\text{ext.})$



- New preliminary world average: $R_{D^*} = 0.284 \pm 0.013$ and $R_{D^0} = 0.356 \pm 0.029$
- Global discrepancy to the SM for $R_{D^0} - R_{D^*}$ at 3.2σ

$R_{J/\psi}$ and R_{Λ_c} with LHCb Run 1 data [PRL 120 121801 (2018), PRL 128 191803 (2022)]

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

with leptonic decay $\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau$

- First LFU test with B_c^+ mesons
- Finding of $B_c^+ \to J/\psi \tau^- \overline{\nu}_\tau$ with 3σ
- Determine form factors from fits to data
- 3D binned template fit to: $\tau_{B_c^+}$, $m^2_{\text{miss.}} = (p_{B_c^+} - p_{J/\psi} - p_\mu)^2$, $(E^*_\mu, q^2 = (p_{B_c^+} - p^2_\mu))$
- Main systematics: sample sizes and form factors

Results

- $R_{J/\psi} = 0.71 \pm 0.17\,(\text{stat.}) \pm 0.18\,(\text{syst.})$
- $R_{J/\psi,\text{SM}} = 0.2583 \pm 0.0038$ [PRL 125 222003 2020]
- Result 2σ above SM prediction

$$R_{\Lambda_c} = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \tau^- \overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}$$

with hadronic decay $\tau^- \to \pi^- \pi^+ (\pi^0) \nu_\tau$

- First LFU test with baryonic $b \to c\ell\nu$ decays
- Largest systematic uncertainty from background template shapes
- Fit variables: t_τ, squared invariant dilepton mass q^2, BDT output for $\Lambda_b^0 \to \Lambda_c^+ \tau^- \overline{\nu}_\tau$

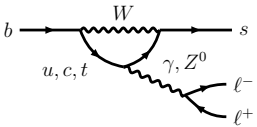
Results

- $R_{\Lambda_c^+} = 0.242 \pm 0.026\,(\text{stat.}) \pm 0.040\,(\text{syst.}) \pm 0.059\,(\text{ext.})$
- $R_{\Lambda_c^+,\text{SM}} = 0.324 \pm 0.004$ [PRD 99 055008]
- 1σ agreement with SM prediction

Lepton flavour universality tests with $b \to s\ell^+\ell^-$ decays

LFU with $b \to s\ell^+\ell^-$ overview

- Rare FCNC $b \to s\ell^+\ell^-$ decays only at loop level: sensitive to NP



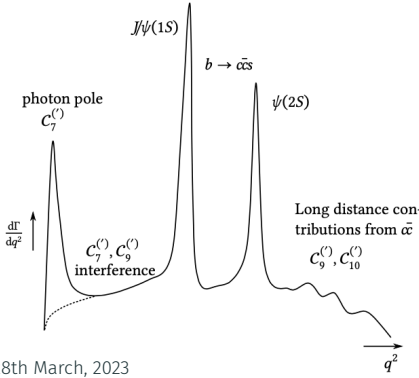
- Use ratios of $b \to s\ell^+\ell^-$ decays with many possible final states

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

- Except different Yukawa couplings and kinematic effects ratios are precisely expected to be unity [PRD 69 (2004) 074020]

- Effective Hamiltonian $\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$
- Study different regions of $q^2 = m^2(\ell^+\ell^-)$

- Decay spectrum of $b \to s\ell^+\ell^-$ processes



R_K and R_{K^*} [arXiv:2212.09153 (submitted to PRD), arXiv:2212.09152 (submitted to PRL)]

- Simultaneous measurement of R_K and R_{K^*} for all years of LHCb data taking in two q^2 regions
  - Low: $q^2 \in [0.1, 1.1]\,\text{GeV}^2/c^4$
  - Central: $q^2 \in [1.1, 6.0]\,\text{GeV}^2/c^4$
- Constrain cross-feed background between two modes in fits to data
- Calibrate simulation with $B^{+/0} \to KJ/\psi(\to \ell^+\ell^-)$ decays: decouple from normalisation mode and enable cross-validation

Measurement strategy to cancel systematic uncertainties

$$R_X = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} \times \underbrace{\frac{\mathcal{B}(B \to KJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to KJ/\psi(\to \mu^+\mu^-))}}_{=1}$$

$$= \underbrace{\left(\frac{\mathcal{N}_{K\mu^+\mu^-}}{\mathcal{N}_{Ke^+e^-}}\right)\left(\frac{\mathcal{N}_{KJ/\psi(\to e^+e^-)}}{\mathcal{N}_{KJ/\psi(\to \mu^+\mu^-)}}\right)}_{\text{Mass fits to LHCb data}} \times \underbrace{\left(\frac{\epsilon_{Ke^+e^-}}{\epsilon_{K\mu^+\mu^-}}\right)\left(\frac{\epsilon_{KJ/\psi(\to \mu^+\mu^-)}}{\epsilon_{KJ/\psi(\to e^+e^-)}}\right)}_{\text{Calibrated simulation samples}}$$

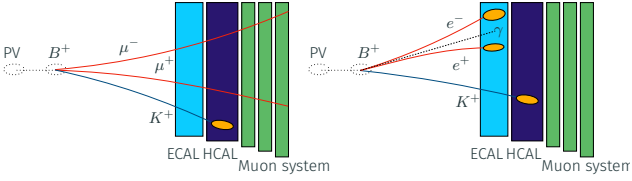
R_K and R_{K^*} [arXiv:2212.09153 (submitted to PRD), arXiv:2212.09152 (submitted to PRL)]

- Mis-ID background: stringent PID requirements for leptons and hadrons
- Multivariate classifiers against partially reconstructed and combinatorial background
- Veto physical backgrounds

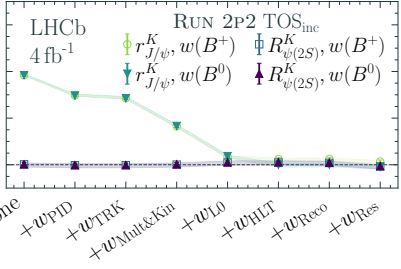
- Validation with charmonium modes:

$$r_{J/\psi} = \frac{\mathcal{B}(B \to KJ/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B \to KJ/\psi(\to e^+e^-))} \equiv 1$$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B \to K\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B \to K\psi(2S)(\to e^+e^-))} \cdot \frac{\mathcal{B}(B \to KJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to KJ/\psi(\to \mu^+\mu^-))}$$



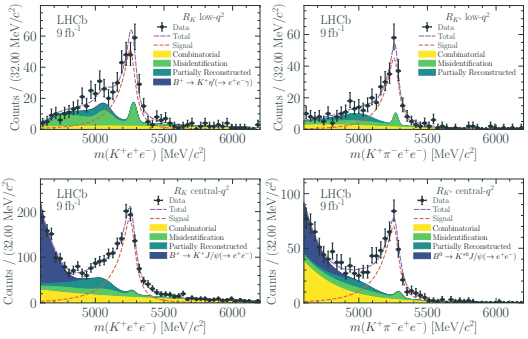
- Trigger independent of $K(\pi)\ell^+\ell^-$ signal as main category to align efficiencies between e and μ modes



[arXiv:2212.09153]

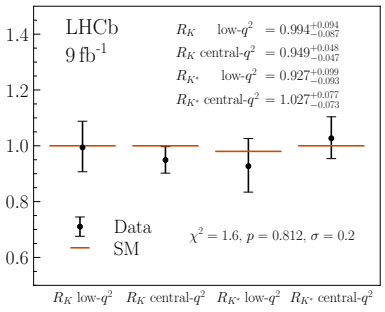
R_K and R_{K^*} [arXiv:2212.09153 (submitted to PRD), arXiv:2212.09152 (submitted to PRL)]

- J/ψ bremsstrahlung tails constrained in rare electron mode fits
- Partially reconstructed $K^{*0}e^+e^-$ background constrained in $K^+e^+e^-$ fit



[arXiv:2212.09153]

- Muon mode consistent to previous analyses



[arXiv:2212.09153]

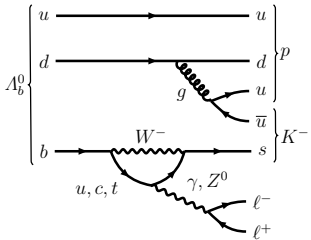
- R_K and R_{K^*} consistent with SM prediction at 0.2σ
- Highest precision of LFU test with $b \to s\ell^+\ell^-$ decays today
- Measurement statistically dominated
- Result supersedes previous LHCb measurements

R_{pK} [JHEP 2020 40 (2020)]

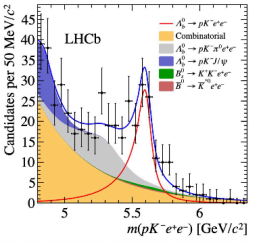
- First LFU test in baryonic sector

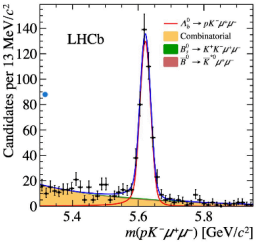
$$R_{pK} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^-\mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^-e^+e^-)}$$

- Test spin dependence of possible NP



- Using LHCb Run 1 and 2016 data



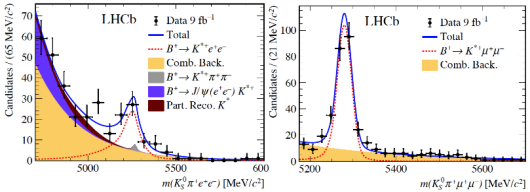


Results

- $R_{pK}^{[0.1,6.0]} = 0.86^{+0.14}_{-0.11}\,(\text{stat.}) \pm 0.05\,(\text{syst.})$
- In agreement with unity within 1σ
- $r_{J/\psi}^{-1} = 0.96 \pm 0.05$
- $R_{\psi(2S)}$ compatible with unity

$R_{K^{*+}}$ and $R_{K^0_S}$ [PRL 128 191802 (2022)]

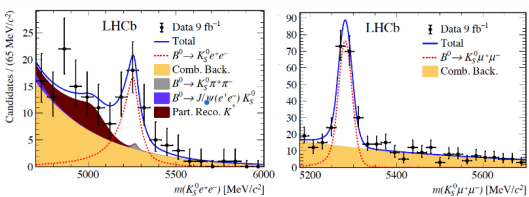
- Using Run 1 + 2 LHCb data set with $B^+ \to K^{*+}(\to K^0_S\pi)\ell^+\ell^-, (\ell = \mu, e)$
- First observation of $B^+ \to K^{*+}e^+e^-$



Result

- $R^{[0.045,6.0]}_{K^{*+}} = 0.70^{+0.18}_{-0.13}\,(\text{stat.})^{+0.03}_{-0.04}(\text{syst.})$
- Compatible with unity within 1.4σ
- $r^{-1}_{J/\psi} = 0.965 \pm 0.011\,(\text{stat.}) \pm 0.032\,(\text{syst.})$
- $R^{-1}_{\psi(2S)}$ compatible with unity

- Using Run 1 + 2 LHCb data set with $B^0 \to K^0_S\ell^+\ell^-$, $(\ell = \mu, e)$
- First observation of $B^0 \to K^0_S e^+e^-$



Result

- $R^{[1.0,6.0]}_{K^{*+}} = 0.66^{+0.20}_{-0.14}\,(\text{stat.})^{+0.02}_{-0.04}(\text{syst.})$
- Compatible with SM within 1.5σ
- $r^{-1}_{J/\psi} = 0.977 \pm 0.008\,(\text{stat.}) \pm 0.027\,(\text{syst.})$
- $R^{-1}_{\psi(2S)}$ compatible with unity

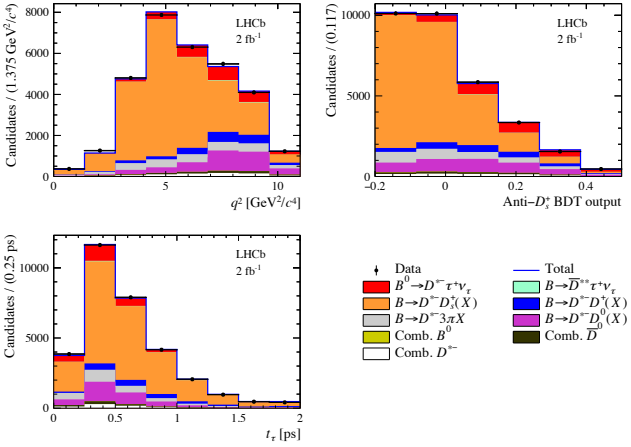
Conclusion

Prospects and conclusion

- **LFU tests with $c\ell\nu$ transitions**
  - First simultaneous measurement of R_{D^0} and R_{D^*} with muonic τ decays at LHCb
  - Very recent update of R_{D^*} hadronic with 2015 - 2016 LHCb dataset
  - Global picture for R_{D^0}-R_{D^*} combination unchanged with SM tension at 3σ level
  - More measurements are in the pipeline: R_{D_s}, R_{D^+},R_{D^*} with $e-\mu$, $R_{D^{**}}$,...
- **LFU tests with $b \to s\ell^+\ell^-$ transitions**
  - R_K and R_K^* are the most precise and accurate LFU tests today
  - These results are compatible with the SM within 0.2σ
  - Many more analyses and updates in the pipeline: R_ϕ,R_Λ, R_{pK},$R_{K\pi\pi}$,...
  - Anomalies in differential branching fractions and angular analyses of the muon modes remain
- Commissioning of LHCb Upgrade I detector ongoing, increased inst. lumi. by factor 5, plan to collect $\sim 50\,\text{fb}^{-1}$ of data in Run 3

Backup

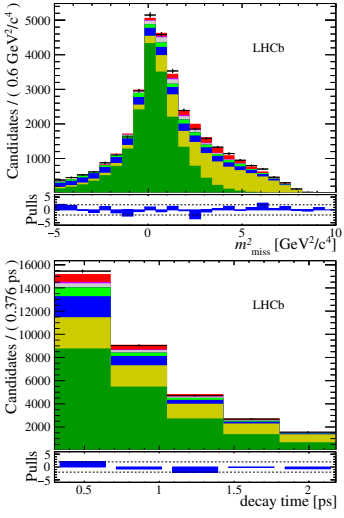
R_{D^*} with hadronic τ decays - Fit projections

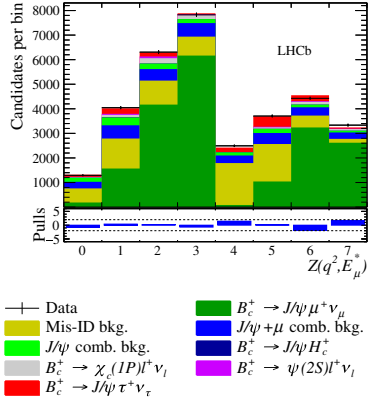


[LHCb-PAPER-2022-052]

- Distributions of the fit variables in the $B^0 \to D^{*0}\tau^+\nu_\tau$ data sample with the fit result overlaid.

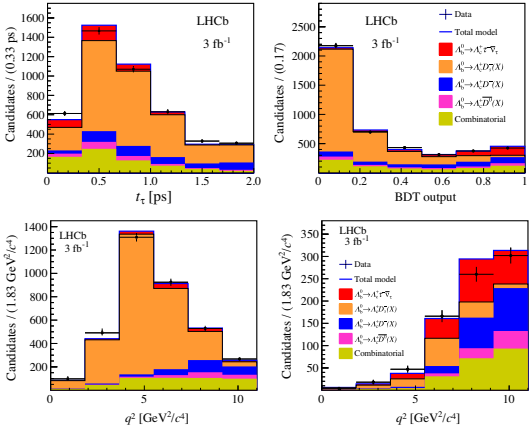
$R_{J/\psi}$ with LHCb Run 1 data - Fit projections





[PRL 120 121801 (2018)]

R_{Λ_c} with LHCb Run 1 data - Fit projections



[PRL 128 191803 (2022)]