Lepton Flavour Universality tests using semileptonic b-hadron decays

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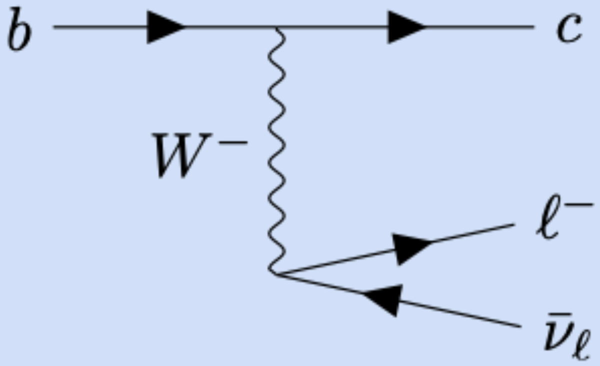
8th International Conference on High Energy Physics in the LHC Era

10/01/2023

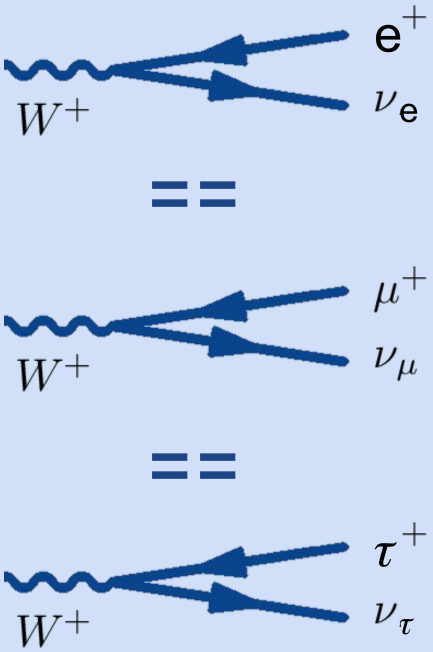
Semileptonic b-hadron decays

$$R \equiv \frac{BR\left(B \rightarrow X_c\, \tau\, \nu_\tau\right)}{BR\left(B \rightarrow X_c\, \ell\, \nu_\ell\right)}$$

- remove the dependence on $|V_{cb}|$
- partial cancellation of theoretical uncertainties related to hadronic effects
- reduce the impact of experimental uncertainties



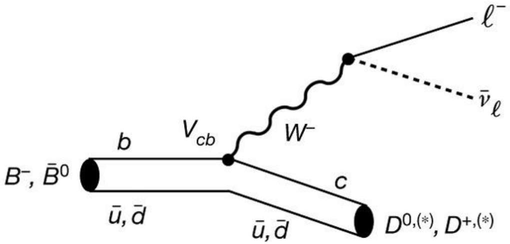
In the Standard Model, gauge bosons couple to leptons independently of their flavour Lepton Flavour Universality (LFU)

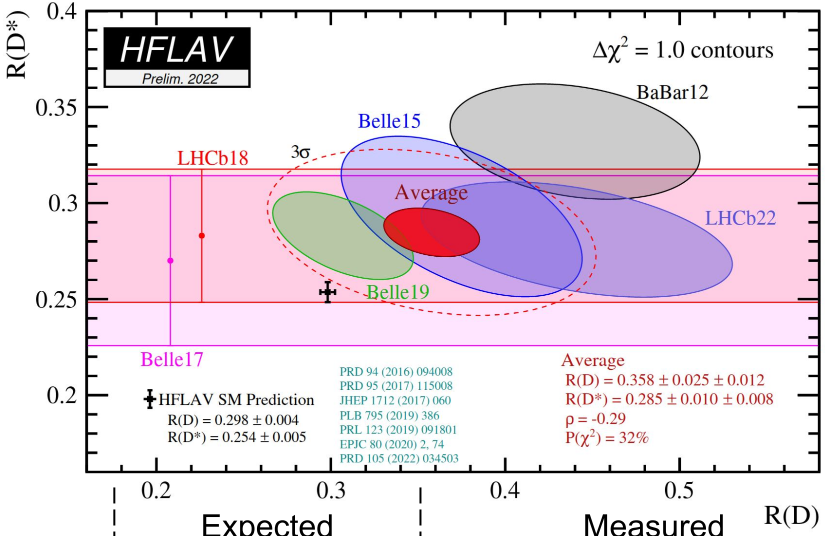


Motivation to look at semileptonic decays

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

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





	Expected	Measured
R(D)	0.298 ± 0.004	0.358 ± 0.025 ± 0.012
R(D)*	0.254 ± 0.005	0.285 ± 0.010 ± 0.008

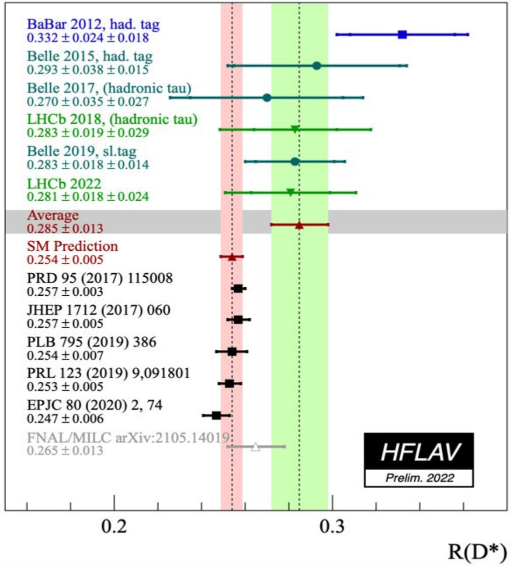
- Measured by three different experiments:
  LHCb, Belle, BaBar
- All point in same direction
- No definitive conclusion yet

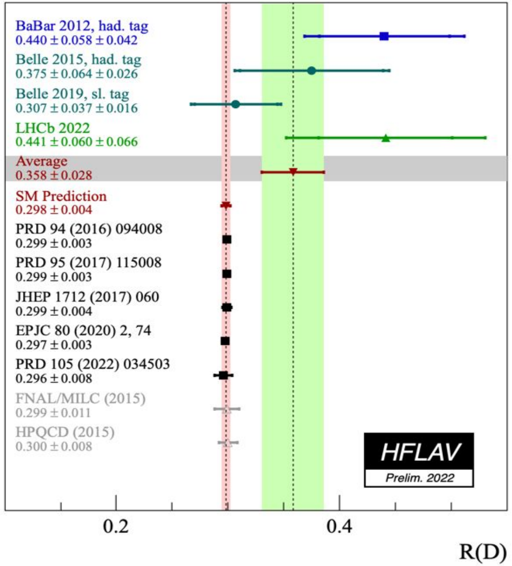
discrepancy from SM of ≈ **3.2 σ** → More measurements are needed!

Semileptonic LFU measurements

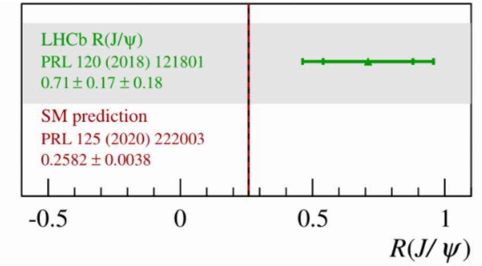
Multiple measurements by B-factories and LHCb using different methods, technics and decay channels

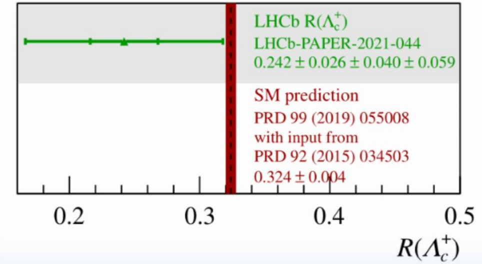
All results show a deviation from Standard Model.





Measurements **SM prediction**





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Semileptonic LFU measurements at LHCb

$R(D^*)$ muonic with $B^0 \to D^{*-}\ell\nu_\ell$ 2015

[PRL 115, 111803]

$R(D^*)$ hadronic with $B^0 \to D^{*-}\ell\nu_\ell$ 2018

[PRL 120, 171802]
[PRD 97, 072013]

$R(J/\psi)$ muonic with $B_c^+ \to J/\psi\ell^+\nu_\ell$ 2018

[PRL 120, 121801]

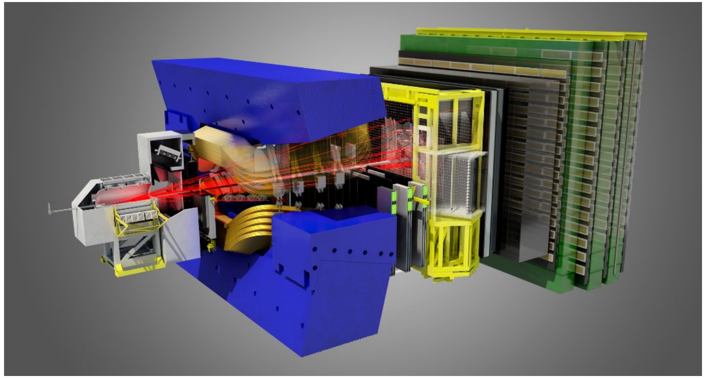
$R(\Lambda_c)$ hadronic with $\Lambda_b \to \Lambda_c^+\ell^-\bar{\nu}_\ell$ 2022

[PRL 128, 191803]

Combined $R(D)$ and $R(D^*)$ muonic 2022

[LHCb-PAPER-2022-039 (in preparation)]

All with 3 fb^{-1} from Run 1



Muons are favoured over electrons at LHCb because of their higher detection efficiency and momentum resolution

$$R \equiv \frac{BR(B \to X_c\tau\nu_\tau)}{BR(B \to X_c\mu\nu_\mu)}$$

Different τ decays

$$R \equiv \frac{BR(B \to X_c \tau \nu_\tau)}{BR(B \to X_c \mu \nu_\mu)}$$

$$B \to X_c^+ \tau^- \overline{\nu_\tau}$$

$$\tau^- \to \pi^- \pi^+ \pi^- \left(\pi^0\right) \nu_\tau$$

PROS:
- presence of only one neutrino
- three charged tracks to reconstruct tau vertex

CONTRAS:
- lower signal yields

$$BR\left(\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau\right) \sim 9.3\%$$

- different final state to normalisation

$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$$

PROS:
- same final state as normalisation
- large signal yields

$$BR\left(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau\right) \sim 17.4\%$$

CONTRAS: difficult to differentiate muon from those originating directly from b-hadron decay

The main approach

Complication

Normalization:

$$B \to X_c^+ \mu^- \bar{\nu}_\mu$$

Cannot be detected

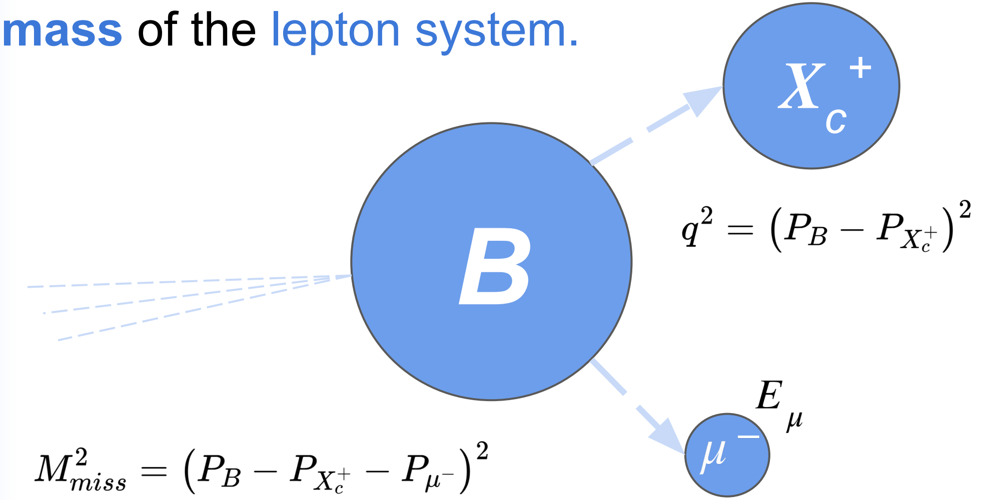
Signal: $\underbrace{\mu^- \nu_\tau \bar{\nu}_\mu}$

$$B \to X_c^+ \tau^- \bar{\nu}_\tau$$

Solution

Fit three-dimensional distributions of B rest frame kinematics:

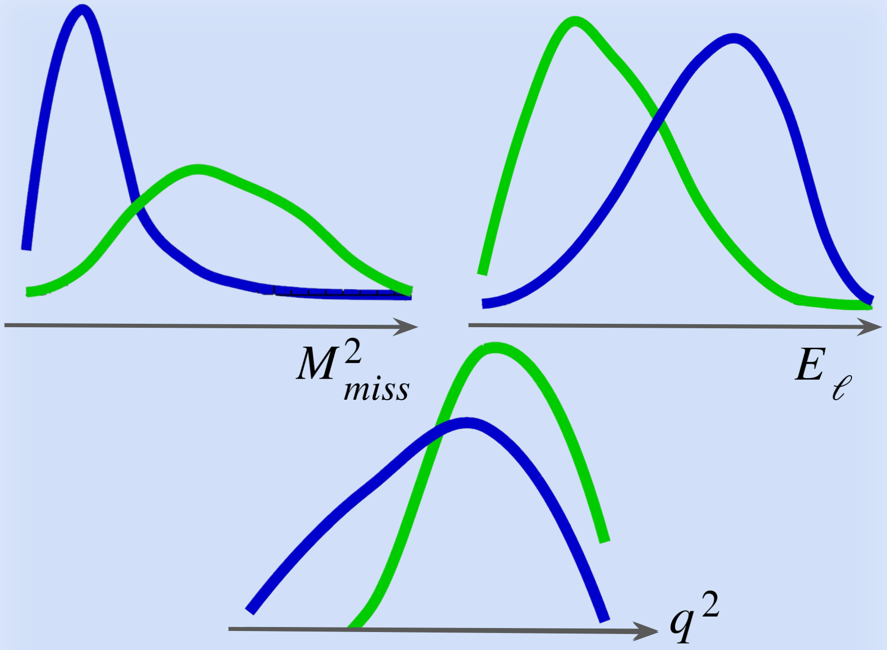
missing mass, **muon energy** and **invariant mass** of the lepton system.



$$q^2 = (P_B - P_{X_c^+})^2$$

$$M^2_{miss} = (P_B - P_{X_c^+} - P_{\mu^-})^2$$

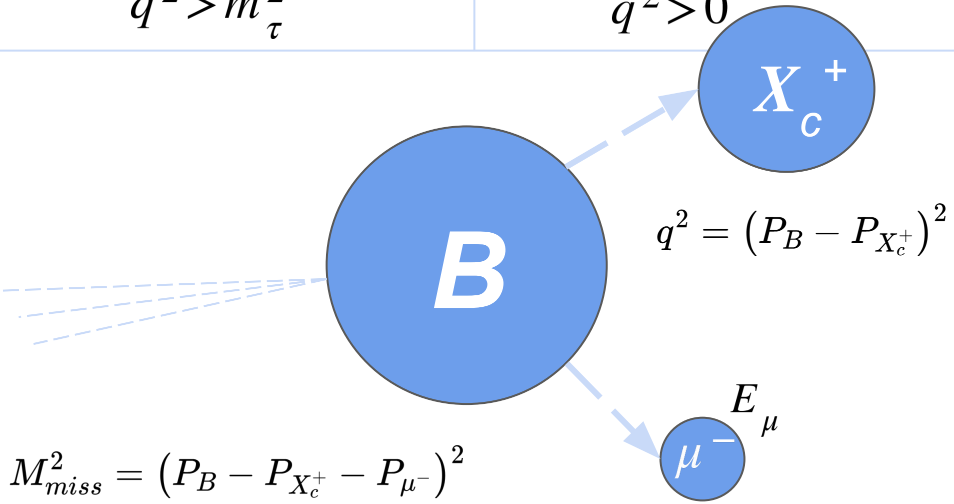
The main approach of the analysis



Signal: $B \to X_c^+ \mu^- \bar{\nu}_\mu \nu_\tau \bar{\nu}_\tau$

Normalization: $B \to X_c^+ \mu^- \bar{\nu}_\mu$

Signal	Normalization
broad spectrum	peak in lower masses
E_μ spectrum is soft	E_μ spectrum is hard
$q^2 > m_\tau^2$	$q^2 > 0$



$$q^2 = (P_B - P_{X_c^+})^2$$

$$M^2_{miss} = (P_B - P_{X_c^+} - P_{\mu^-})^2$$

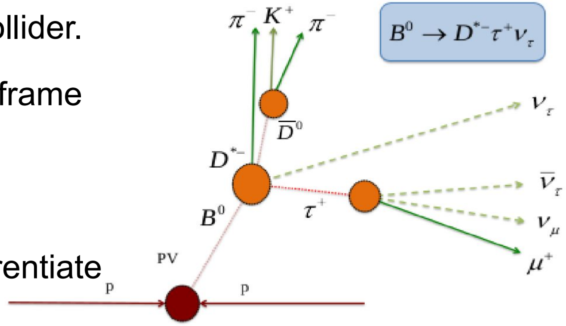
$R(D^*)$ muonic at LHCb

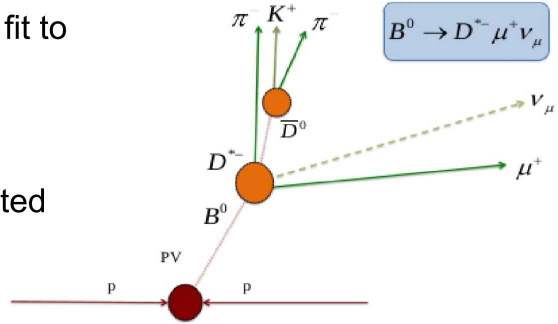
$$R(D^*) = \frac{BR(B \to D^* \tau \nu_\tau)}{BR(B \to D^* \mu \nu_\mu)}, \quad \tau \to \mu \nu_\mu \nu_\tau\,, \quad D^* \to D(\to \pi K)\pi$$

- The first semileptonic LFU measurement at the hadron collider.
- Unknown rest frame -> use approximation to access rest frame kinematics
  - assume $\gamma\beta_{z,visible} = \gamma\beta_{z,total}$
  - ~20% resolution on B momentum sufficient to differentiate signal/normalisation.
- Separate signal and normalisation channel with a 3D template fit to kinematic variables:

$$M^2_{miss} \qquad E^*_\mu \qquad q^2$$

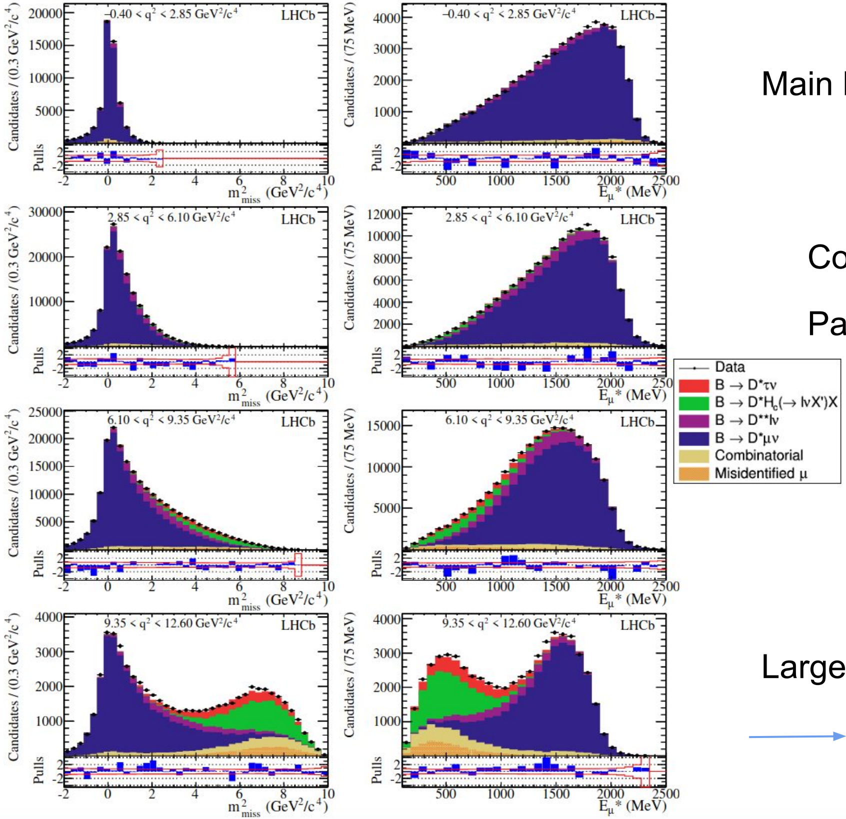
- Simulation templates : signal, normalisation, partially reconstructed contributions
- Data templates : Combinatorial, mis-ID





$R(D^*)$ muonic at LHCb

2015
Run 1 data, 3 fb^{-1}
[PRL 115, 111803]



Main background:

$$B \to D^{**}\mu\nu$$
$$B \to D^* X_c(\to X\mu\nu)X$$

Combinatorial background

Particle misidentification background

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

2.1σ above SM

Largest systematic uncertainties →

→ the size of simulated samples and $\mu \longleftrightarrow \pi$ misidentification

$R(D^*)$ hadronic at LHCb

$$R(D^*) = \frac{BR(B \to D^* \tau \nu_\tau)}{BR(B \to D^* \mu \nu_\mu)}, \quad \tau \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau \,, \; D^* \to D(\to \pi K)\pi$$

- $B \to D^{*-} \pi^+ \pi^- \pi^+$ used as normalisation mode

$$R(D^*) = \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{1}{BR(\tau \to 3\pi^\pm (\pi^0) \nu_\tau)} \times \left[\frac{BR(B \to D^* 3\pi^\pm)}{BR(B \to D^{*-} \mu^+ \nu_\mu)} \right]_{external}$$

- 3D binned template fit to kinematic variables to extract signal:

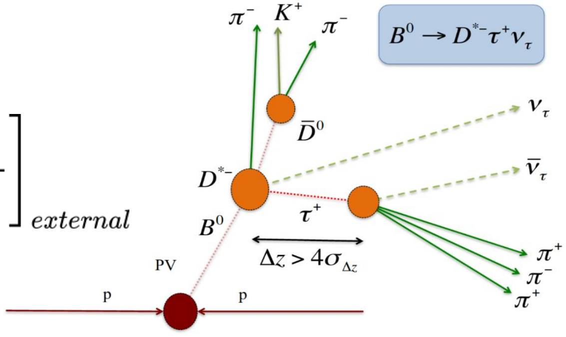
  q^2

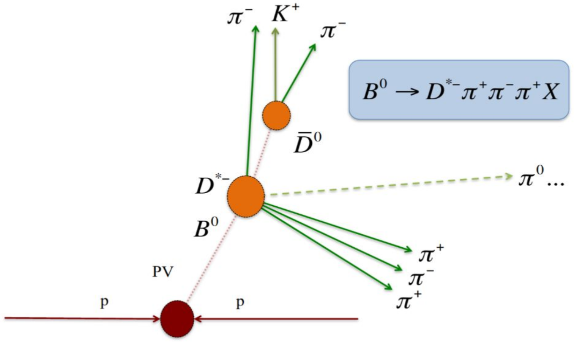
  τ decay time

  output of BDT trained to discriminate τ from D_s

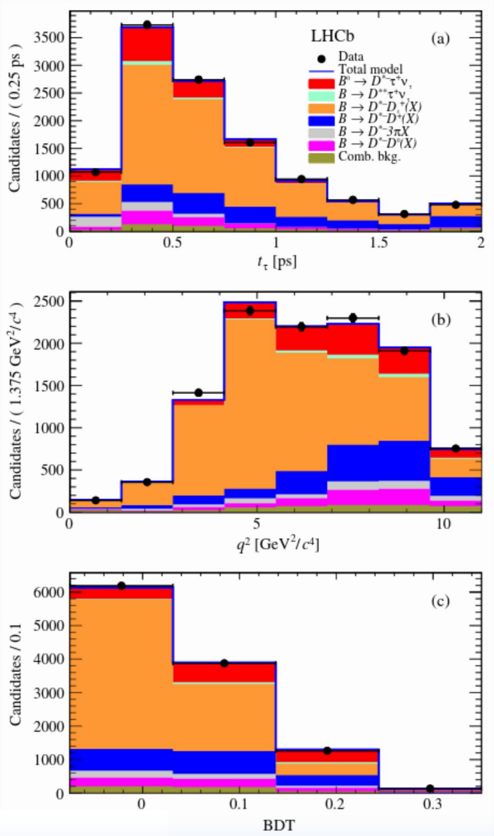
- Fit to the invariant mass of the $D^* 3\pi$ system around the B mass to extract normalisation.

- Only one neutrino emitted at the τ vertex that allows the vertex reconstruction.





$R(D^*)$ hadronic at LHCb



2018
Run 1 data, 3 fb^{-1}
[PRL 120, 171802],
[PRD 97, 072013]]

Main background:

$B \to D^* 3\pi^\pm X$

$B \to D^* D_s^+ X$

suppressed with BDT based on kinematics and resonant structure

suppressed by requiring the τ vertex to be downstream wrt B vertex along beam direction with a 4σ significance

$$R(D^*) = 0.280 \pm 0.018(stat) \pm 0.026(sys) \pm 0.013(ext)$$

1σ above SM

Largest systematic uncertainties →

→ the size of simulated samples, double-charm background, efficiency ratio

$R(J/\psi)$ muonic at LHCb

$$R(J/\psi) = \frac{BR(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{BR(B_c^+ \to J/\psi\,\mu\nu_\mu)}, \quad \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau\,, \quad J/\psi \to \mu^+\mu^-$$

2018
Run 1 data, 3 fb^{-1}
[PRL 120, 121801]

- LFU test with different spectator quark.
- Separate signal and normalisation channel with a 3D template fit to kinematic variables:

$$M^2_{miss}$$

$$\left.\begin{array}{l} q^2 \\ E^*_\mu \text{ (}B\text{rest frame)} \end{array}\right\} Z(q^2, E^*_\mu)$$

B_c decay time

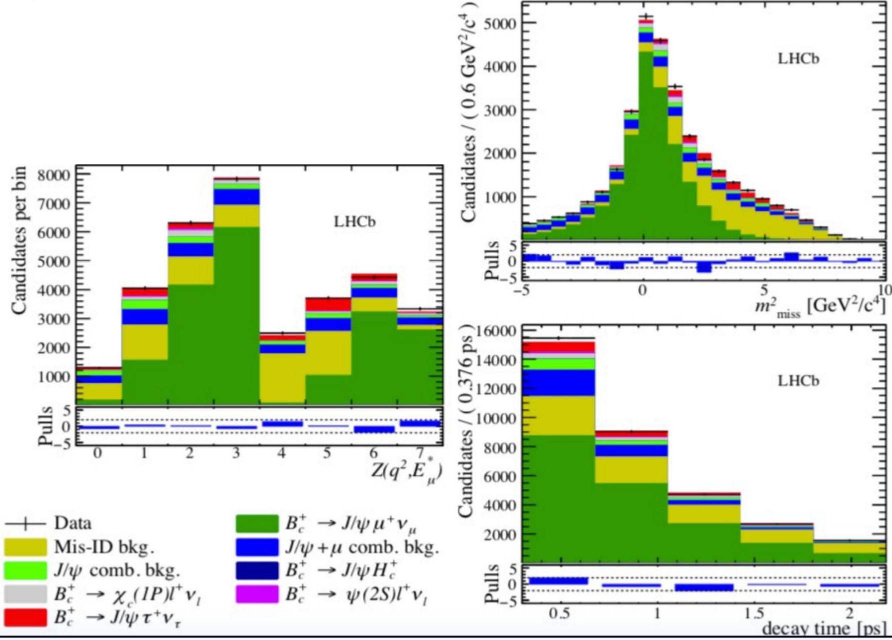
- Main background $B_c \to J/\psi X$ and $\mu \leftrightarrow \pi$ mis-ID.

$$\boxed{R(J/\psi) = 0.171 \pm 0.17(stat) \pm 0.18(sys)}$$

2 σ above SM

Largest systematic uncertainties →

→ the size of simulated samples and B_c^+ form factors.



$R(\Lambda_c)$ hadronic at LHCb

$$R(\Lambda_c^+) = \frac{BR(\Lambda_b \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{BR(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}, \quad \tau^- \to 3\pi^\pm(\pi^0)\bar{\nu}_\tau\,, \;\; \Lambda_c^+ \to pK^-\pi^+$$

2022
Run 1 data, 3 fb^{-1}
[PRL 128, 191803]

- First LFU test in baryonic $b \to cl\nu$ decay.
- $\Lambda_b \to \Lambda_c^+\pi^-\pi^+\pi^-$ used as normalisation mode.

$$R(\Lambda_c^+) = \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{1}{BR(\tau \to 3\pi^\pm(\pi^0)\nu_\tau)} \times \left[\frac{BR(\Lambda_b \to \Lambda_c^+ 3\pi^\pm)}{BR(\Lambda_b \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}\right]_{external}$$

- 3D binned template fit to kinematic variables to extract signal:

q^2

τ decay time

output of BDT trained to distinguish $\Lambda_b \to \Lambda_c^+ D_s^-(X)$ decay.

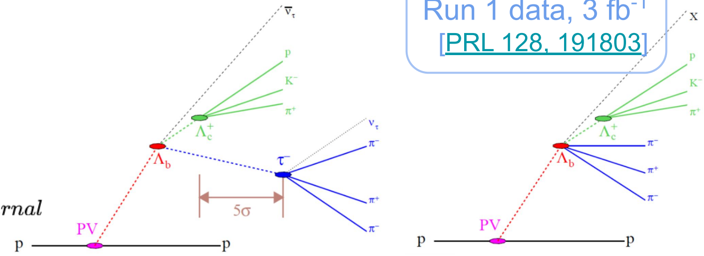
- Main background $\Lambda_b \to \Lambda_c^+ 3\pi^\pm X$ and $\Lambda_b \to \Lambda_c^+ D_{(s)}(\to 3\pi^\pm X)X$

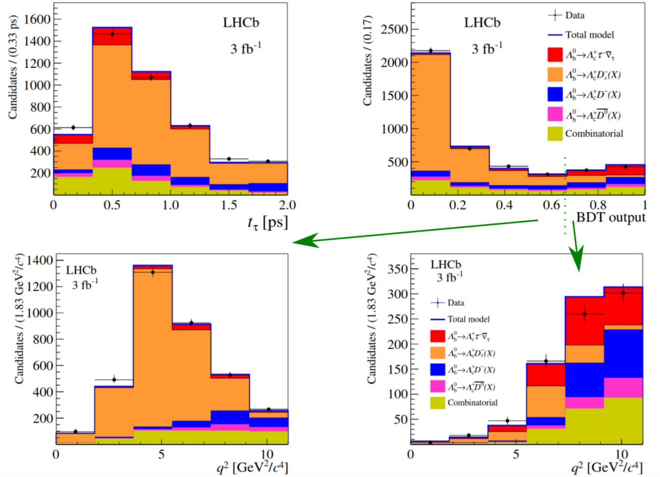
$$R(\Lambda_c^+) = 0.242 \pm 0.026(stat) \pm 0.040(sys) \pm 0.059(ext)$$

Agreement within 1σ

Largest systematic uncertainties →

→ the double-charm background templates





Combined $R(D)$ and $R(D^*)$ muonic at LHCb

2022
Run 1 data, 3 fb^{-1}
First joint measurement of \$R(D^*)\$ and \$R(D^0)\$ at LHCb

$$R\left(D^{(*)}\right) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}, \quad \tau \to \mu\nu_\mu\nu_\tau\,, \; D^* \to D(\to \pi K)\pi$$

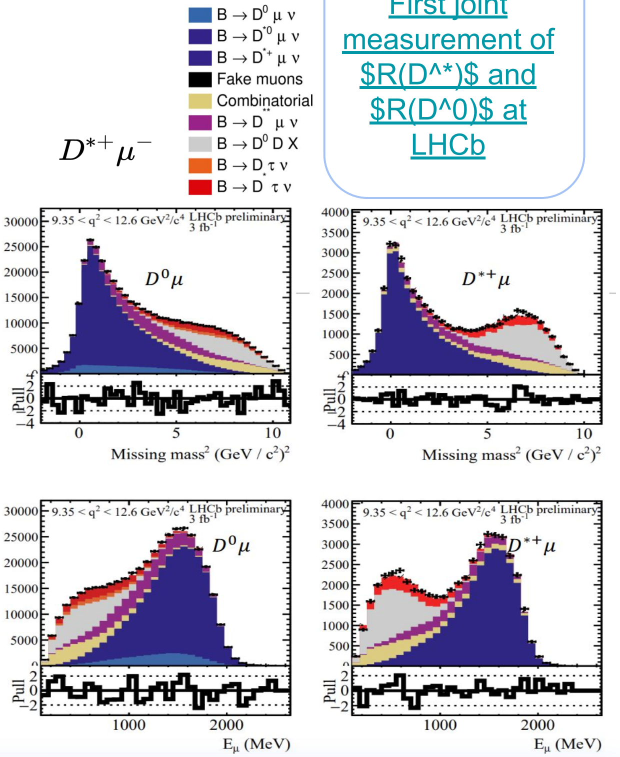
- extend LHCb Run1 muonic measurement from 1D band to 2D ellipse via a simultaneous fit to disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples.
- Higher branching fractions and higher efficiency due to inclusion of not fully reconstructed D^*
- Using rest frame approximation, construct 3D "template" histograms for each process contributing.
- 8-way simultaneous maximum-likelihood fit to (2x) isolated signal regions, (2x3x) anti-isolated control regions

$$\boxed{\begin{aligned} R(D^*) &= 0.281 \pm 0.018(stat) \pm 0.024(sys) \\ R(D) &= 0.441 \pm 0.060(stat) \pm 0.066(sys) \end{aligned}}$$

1.9 σ above SM

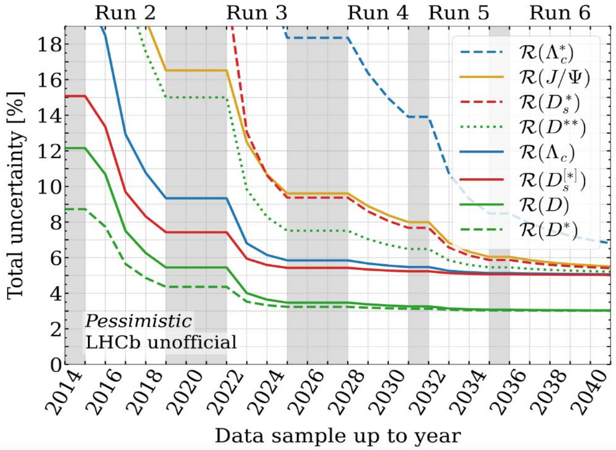
Largest systematic uncertainties →

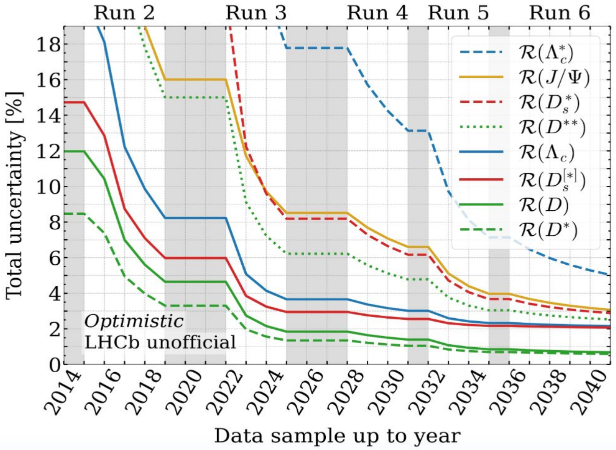
→ the size of simulated samples and the effects of shape parameters derived from control regions



Future prospects

- Significant reduction in statistical uncertainties. $Run1 + Run2 = 4 \times Run1$
- Reduction in systematic uncertainties due to
  - Improvements in simulation techniques and hardware.
  - Better knowledge of background channels.
  - Improved external uncertainties thanks to new measurements.
  - New theory inputs
- Future and ongoing measurements, including angular analysis : $R(\Lambda_c)$ muonic $R(D^+)$ $R(D^{**})$ $R(\Lambda_c^*)$ $R(D^*)$(with e -μ) $R(D_s)$
- Update of measurements with Run2





Conclusions

- Lepton Flavour Universality tests are a clean probe to NP, complementing the direct researches.

- Study of semileptonic B decays at LHCb very challenging due to the missing neutrinos and no beam-energy constraint.

- The LHCb experiment has performed several $b \to c l \nu_l$ measurements that hint on tension with SM: $R\left(D^{(*)}\right)$, $R(J/\psi), R(\Lambda_c)$

- More measurements to come!