Lepton Flavour Universality tests using semileptonic b-hadron decays

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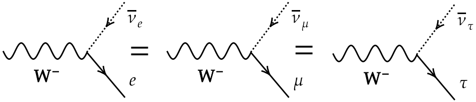
Genova, Italy

Introduction

Lepton Flavor Universality

In the Standard Model (SM), the weak interactions towards three generations of leptons are identical.



This assumption is known as **Lepton Flavor Universality (LFU)**.

- New physics may be more sensible to the 3rd family
- Need to cancel for theoretical uncertainties

Reason for measuring ratios of branching fractions.

To test the LFU, we measure:

- Charged current $b \to c\ell\nu_\ell$:

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

  where: $X_b = B^0, B^+_{(c)}, B^0_s, \Lambda_b, \ldots \; X_c = D^{(*)}, J/\psi, D_s, \Lambda_c, \ldots$

  - Main contribution: Tree-level digaram

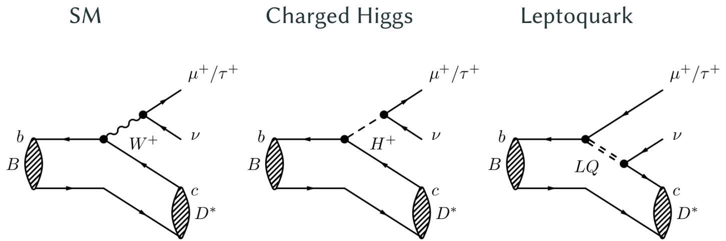
- Or $b \to s\ell\ell$ neutral transitions:

$$R(X_s) = \frac{\mathcal{B}(X_b \to X_s\, \mu^+\mu^-)}{\mathcal{B}(X_b \to X_s\, e^+e^-)}$$

  where: $(X_b, X_s) = (B^0, K^{*0})$ or (B^+, K^+)

  - Main SM contribution: Penguin or box diagrams

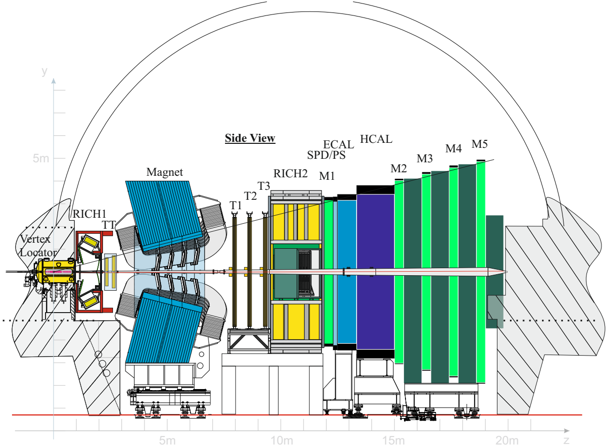
New Physics behind LFU violation?



There are three typical candidates to account for the $R(D)$ and $R(D^*)$ anomalies:

- Leptoquarks [PRL 116, 081801, PRD 94, 115021, ...]
- Two-Higgs-doublet models [PRL 116, 081801, ...]
- Heavy vector bosons, *e.g.* W' [JHEP 07 (2015) 142 1506.01705, ...]

LHCb experiment



- Excellent vertex resolution
  - xy-plane: $10 - 40\ \mu m$
  - z-axis: $50 - 300\ \mu m$
  - τ^{+} lifetime resolution 0.4 ps
- Particle identification efficiencies:
  - $\sim 97\%$ for μ, e
  - $\sim 3\%$ pion misidentification
  - Good separation between π, K, p

[JINST 3 (2008) S08005, Int. J. Mod. Phys. **A30**, 1530022 (2015)]

$R(X_c)$ measurements at LHCb – Overview

LFU test using semileptonic decays ($b \to c\ell\nu_\ell$)

- Approximation needed for B reconstruction (due to missing neutrinos)
- Couple of background sources

Measurements with:

a) **Hadronic** τ^+ decays: $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- $R(D^*)$ (Run 1 and partial Run 2 data)
- $R(\Lambda_c)$ (Run 1 data)

[PRL **120**, 171802 (2018), PRD **97**, 072013 (2018), PRL **128**, 191803 (2022), arXiv:2305.01463]

b) **Muonic** τ^- decays: $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$

- $R(D^*)$, $R(J/\psi)$ (Run 1 data)
- $R(D)$–$R(D^*)$ (Run 1 data)

[PRL **115**, 111803 (2015), PRL **120**, 121801 (2018), arXiv:2302.02886]

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- $R(D^*)$ (Run 1 and partial Run 2 data) $\leftarrow$ **This talk**
- $R(\Lambda_c)$ (Run 1 data) $\leftarrow$ **This talk**

[PRL **120**, 171802 (2018), PRD **97**, 072013 (2018), PRL **128**, 191803 (2022), arXiv:2305.01463]

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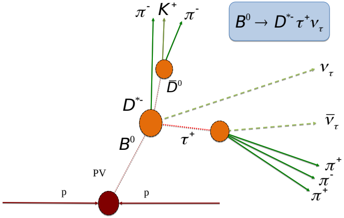
- $R(D)$–$R(D^*)$ (Run 1 data) $\leftarrow$ **This talk**

[PRL **115**, 111803 (2015), PRL **120**, 121801 (2018), arXiv:2302.02886]

$R(D^*)$ measurements at LHCb - two complementary τ decay channels

Hadronic τ^+ decay



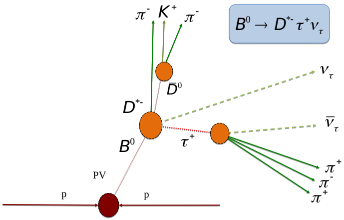
$\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- Measuring τ^+ decay **position** to suppress dominant backgrounds
- **High purity sample**
- **Specific dynamics of $\tau^+ \to 3\pi^\pm\bar{\nu}_\tau$**
- $R(X_c)$ requires external inputs
- Lower statistics

[arXiv:2305.01463]

$R(D^*)$ measurements at LHCb - two complementary τ decay channels

Hadronic τ^+ decay



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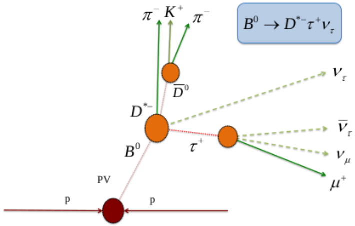
[arXiv:2305.01463]

Muonic τ^+ decay



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

- **Direct measurement of** $R(X_c)$
- **High statistics**
- Backgrounds from D^+ must be controlled well
- Sensitive to $D^{**}\mu^-\nu_\mu$

[arXiv:2302.02886]

$R(D^*)$ with hadronic τ decays

$R(D^*)$ hadronic – methodology

$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}}_{\mathcal{K}(D^*)} \times \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}}_{\text{External branching fractions}}$$

We measure:

$$\mathcal{K}(\mathcal{D}^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \frac{1}{\mathcal{B}(\tau^+ \to 3\pi^\pm\overline{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi^\pm(\pi^0)\bar{\nu}_\tau)}$$

$R(D^*)$ hadronic – methodology

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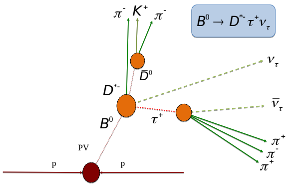
- N_{sig} from a 3D binned template fit:
  - $q^2 = (p_B - p_{D^*})^2$ momemtum transfered to the leptonic system (8 bins),
  - τ^+ lifetime t_τ (8 bins),
  - Anti-D_s^+ BDT (6 bins).
- N_{norm} from an unbinned fit to $m(D^* 3\pi^\pm)$
- Efficiences ε_{sig} and $\varepsilon_{\text{norm}}$ extracted from MC samples

[arXiv:2305.01463]

Signal & Normalisation mode

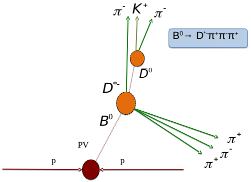
Signal mode



$$B^0 \to D^{*-}\tau^+\nu_\tau \text{ and } \tau^+ \to 3\pi^\pm(\pi^0)\bar{\nu}_\tau$$

- Same final states in signal and normalisation modes
- Signal mode partially reconstructed
    - Missing neutrinos

Normalisation mode



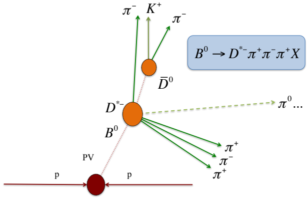
$$B^0 \to D^{*-}3\pi^\pm$$

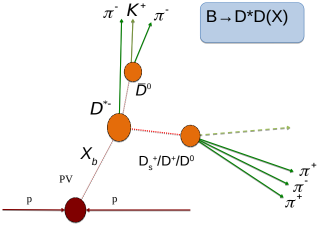
- Normalisation mode fully reconstructed
- Helps to cancel out systematic uncertainties

[arXiv:2305.01463]

$R(D^*)$ with hadronic τ decays – Background

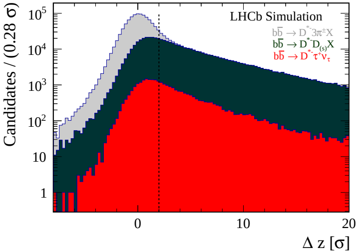
- The most dominant background is the prompt decay $B \to D^{*-} 3\pi^{\pm} X$
  - The $3\pi^{\pm}$ directly from B meson
  - Around $\sim 100\times$ signal decays
- The second largest contribution from double charm decays $B \to D^{*-} D X$
  - $D = D_s^+, D^+, D^0$
  - Signal like topology with a detached vertex due to non-negligible lifetime
  - $B \to D^{*-} D_s^+ X \sim 10\times$ signal decays

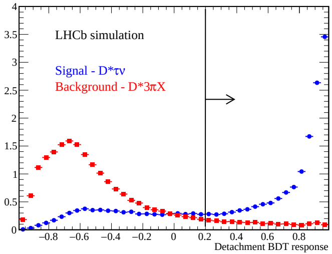




[arXiv:2305.01463]

$R(D^*)$ with hadronic τ decays – Selection



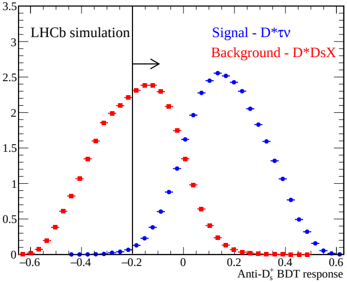


- Detachment criteria: $B \to D^{*-}3\pi^{\pm}X$ suppressed by requiring the $\boldsymbol{\tau}$ vertex to be *downstream* w.r.t. the $\boldsymbol{B}$ vertex along the beam direction

- A BDT classifier is used along with the vertex separation variables $\Rightarrow$ **background rejection > 99 %**

[arXiv:2305.01463]

$R(D^*)$ with hadronic τ decays – Selection

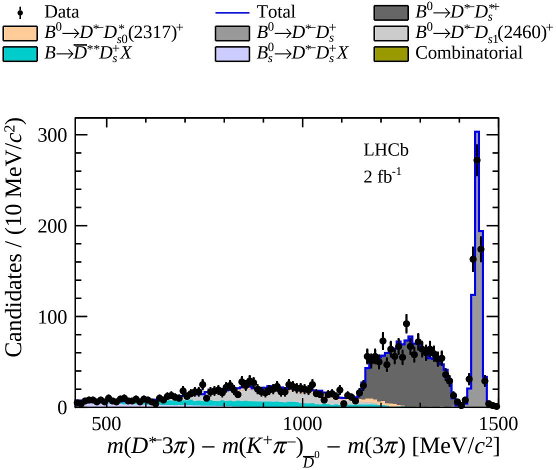


- Detachment criteria: $B \to D^{*-} 3\pi^{\pm} X$ suppressed by requiring the $\boldsymbol{\tau}$ vertex to be *downstream* w.r.t. the $\boldsymbol{B}$ vertex along the beam direction
- A BDT classifier is used along with the vertex separation variables $\Rightarrow$ **background rejection > 99 %**
- Another BDT classifier based on kinematics and resonant structure to separate signal from $B \to D^{*-} D_s^+ X$
  - This BDT output is one of the fit variables

[arXiv:2305.01463]

Production of D_s^+ in $B \to D^{*-} D_s^+ X$

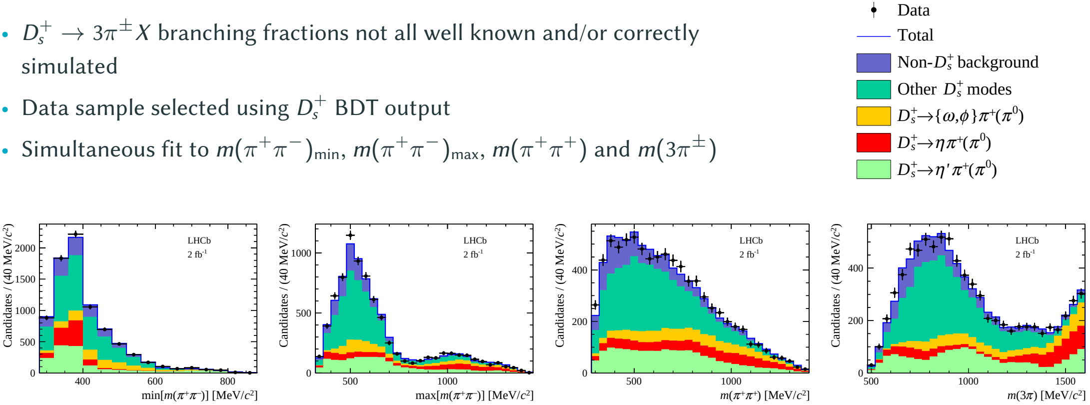
- $B \to D^{*-} D_s^+ X$ decays produced in a spectrum of $B \to D^{*-} D_s^{+(*,**)} X$ processes
- Rare knowledge about the fraction of each process
- Enriched data sample of double charm decays with fully reconstructed $D_s^+ \to 3\pi^\pm$ process
- Fit to $m(D^{*-} 3\pi)$
- Fractions of each component determined and used as constraints in the signal extraction fit
- Projections of data and simulations on the fit variables shows a good agreement



[arXiv:2305.01463]

Decays of D_s^+ in $B \to D^{*-} D_s^+ X$

- $D_s^+ \to 3\pi^{\pm} X$ branching fractions not all well known and/or correctly simulated
- Data sample selected using D_s^+ BDT output
- Simultaneous fit to $m(\pi^+\pi^-)_{\text{min}}$, $m(\pi^+\pi^-)_{\text{max}}$, $m(\pi^+\pi^+)$ and $m(3\pi^{\pm})$



- The fractions of various modes extracted and simulation corrected accordingly

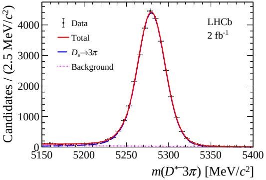
[arXiv:2305.01463]

Signal & normalisation fit results

[arXiv:2305.01463]

- Normalisation yield from a fit to $m(D^{*-}3\pi^{\pm})$:

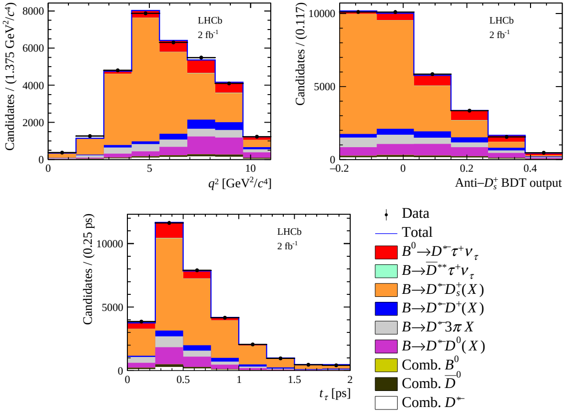
$$N_{B^0 \to D^{*-}3\pi^{\pm}} = 30540 \pm 182$$



- Signal yield from a 3D-binned template fit:
  - $q^2 \equiv (p_{B^0} - p_{D^*})^2$
  - τ^+ lifetime
  - Anti-D_s^+ BDT output

$$N_{B^0 \to D^{*-}\tau^+\nu_\tau} = 2469 \pm 154$$

(Run 1: $N_{B^0 \to D^{*-}\tau^+\nu_\tau}$ = 1296 $\pm$ 86)



Larger dataset and improved selection with respect to Run1 with hadronic τ^+ analysis

Systematic uncertainties

Dominant sources of systematics are

- Signal and background modelling
- Selection criteria on $B^0 \to D^{*-}\tau^+\nu_\tau$ and $B^0 \to D^{*-}3\pi^\pm$ decay modes
- Limited size of the simulation samples
- Empty bins in the templates

[arXiv:2305.01463]

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-}D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-}D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\bar{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-}D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-}D^0(X)$ template shapes	1.2
$B \to D^{*-}D_s^+(X)$ template shapes	0.3
$B \to D^{*-}3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

$R(D^*)$ with hadronic τ decays – final result

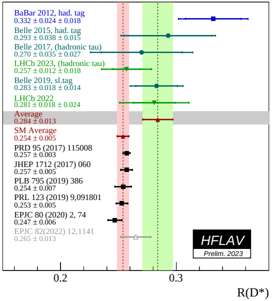
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

We measure the absolute branching fraction of $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.23 \pm 0.07(\text{stat}) \pm 0.08(\text{syst}) \pm 0.05(\text{ext})) \times 10^{-2}$$

Leading to

$$R(D^*)_{2015-2016} = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$$



[HFLAV]

Combining with the Run 1, the **hadronic** result, **we obtain an agreement to SM within 1σ**

$$R(D^*)_{2011-2016} = 0.257 \pm \underbrace{0.012}_{\text{stat}} \pm \underbrace{0.014}_{\text{syst}} \pm \underbrace{0.012}_{\text{ext}}$$

One of the most precise measurements of $R(D^*)$

[arXiv:2305.01463]

$R(D)$–$R(D^*)$ with muonic τ decays

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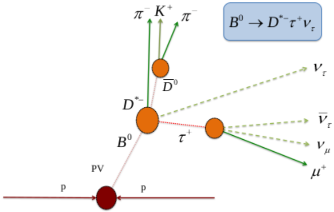
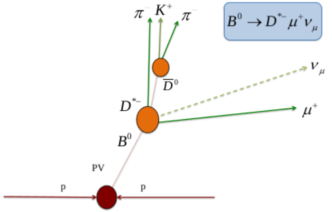
[arXiv:2302.02886]

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with **Run 1** data
  - **Muonic** channel $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
- No narrow peak to fit (3 neutrinos in final state)
- Backgrounds : partially reconstructed B decays
  - $B \to D^* \mu\nu$, $B \to D^{**} \mu\nu$, $B \to D^* DX$ with $D \to \mu X$, ...
- Select $D^0\mu^-$ and $D^{*+}\mu^-$ candidates where
  - $D^0 \to K^-\pi^+$, $D^{*+} \to D^0\pi^+$
  - Reconstructed $D^{*+} \to D^0\pi^+$ is vetoed in $D^0\mu^+$ sample
- Trigger on D^0 - preserve acceptance for soft muons
- Custom muon ID classifier, flatter in kinematic acceptance
  - Reduces misID background





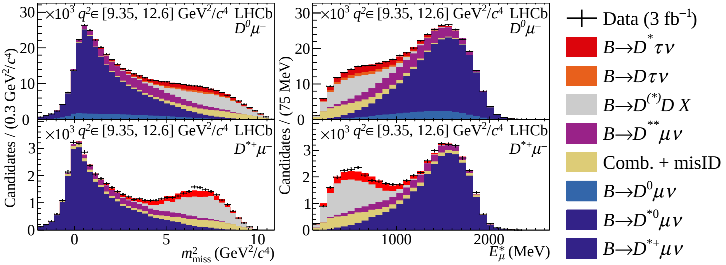
$R(D)$–$R(D^*)$ with muonic τ decays

[arXiv:2302.02886]

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data using **muonic** $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

3D template fit to

- $q^2 \equiv (p_B - p_{D^*})^2$
- $m^2_{\text{miss}} \equiv (p_B - p_{D^*} - p_\mu)^2$
- E^*_μ energy of μ

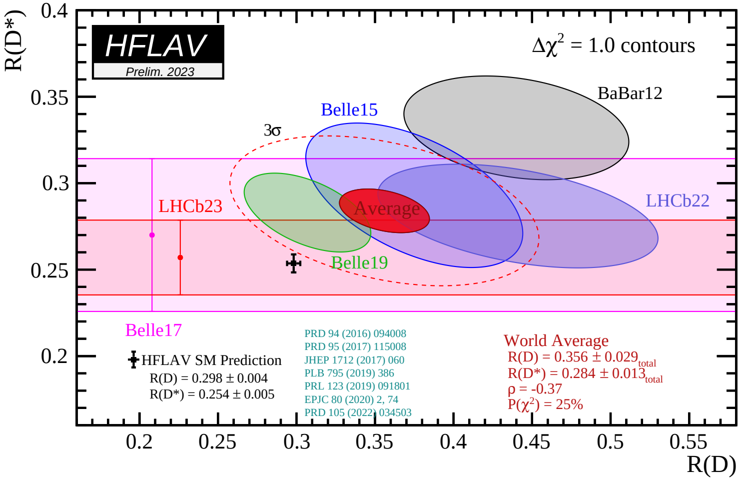


$$\begin{cases} R(D) & = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst}) \\ R(D^*) & = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst}) \end{cases}$$

Agreement with SM within 1.9σ

$R(D)$–$R(D^*)$ world average

[HFLAV]



- The world average becomes

$$\begin{cases} R(D^*) &= 0.284 \pm 0.013 \\ R(D) &= 0.356 \pm 0.029 \end{cases}$$

- The deviation w.r.t. the SM is at **3.2σ** for the combination of $R(D)$–$R(D^*)$

$R(\Lambda_c)$ with hadronic τ decays

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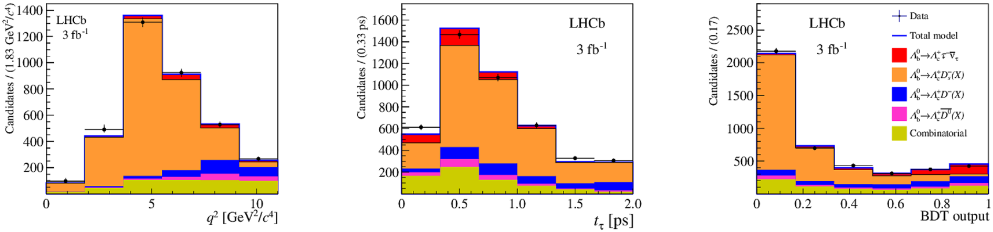
- First LFU test in a **baryonic** $b \to c\ell\nu_\ell$ decay with Run 1 data using **hadronic** $\tau^+ \to 3\pi^\pm(\pi^0)$
- Normalisation channel $\Lambda_b^0 \to \Lambda_c^+ 3\pi^\pm$

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

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

- 3D template fit to extract signal yield



$R(\Lambda_c)$ with hadronic τ decays

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

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

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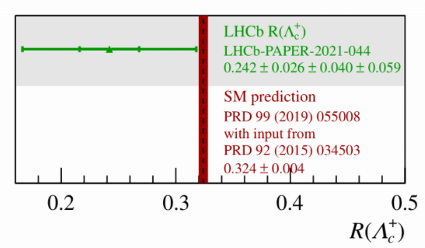


$$\begin{cases} \mathcal{K}(\Lambda_c^+) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst}) \\ R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext}) \end{cases}$$

Agreement within 1.0σ to SM

[PRL **128**, 191803 (2022)]

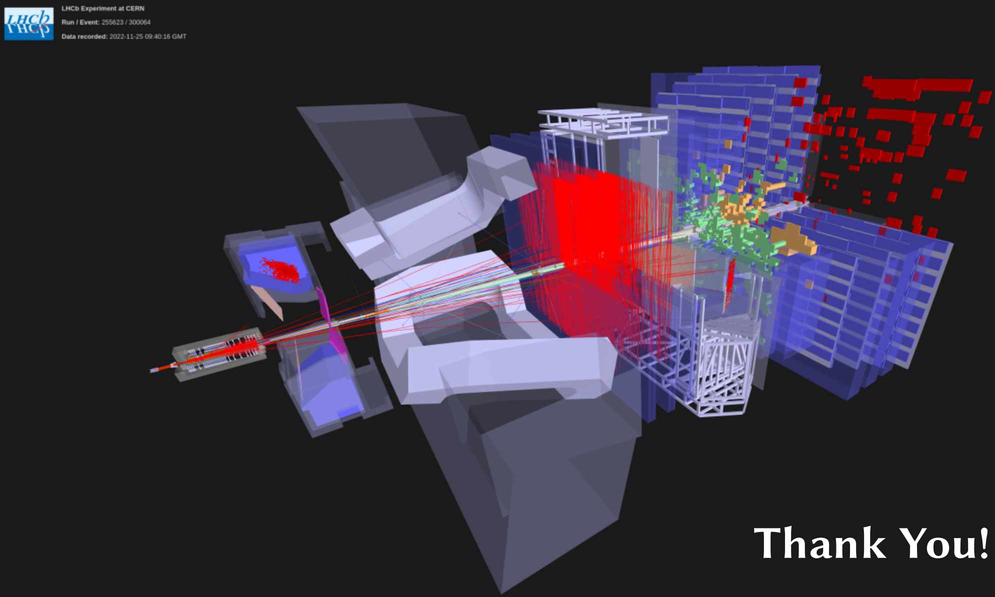
Conclusions

Conclusions

- Recent results from **semileptonic** to test LFU at LHCb
  - $R(D^*)$ with hadronic τ decays (using Run 1 and partial Run 2 data)
  - $R(D)$–$R(D^*)$ with muonic τ decays
  - $R(\Lambda_c)$ with hadronic τ decay
- The combined $R(D)$–$R(D^*)$ is still at 3.2σ tension from the SM

Stay tuned:

- $R(D^*)$ with hadronic τ^+ decays using **Run 1 and Run 2** datasets
  - Expected statistical uncertainty of the order of 3%
    (while: 6.7% for **Run 1** only and for 5% **Run 1 and partial Run 2**)
  - Many systematics will reduce with larger samples
  - The recent BESIII results [PRD **107**, 032002 (2023), arXiv:2212.13072] on inclusive $D_{(s)}^{(0,+)} \to 3\pi^{\pm} X$ could reduce the systematic uncertainties in the legacy measurement to come
- Many more analyses to come: $R(D^0)$, $R(D^+)$, $R(D_s^+)$, $R(D^*)_e$ and *angular analysis* to determine spin structure of potential NP
- We have started taking data with first upgrade of LHCb, exciting time ahead!

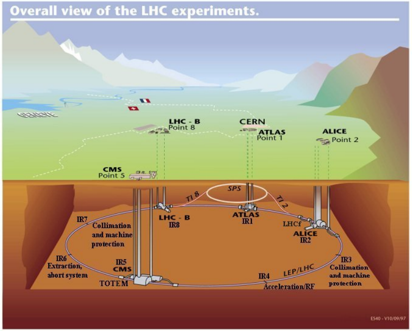

LHCb
LHCb Experiment at CERN
Run / Event: 255623 / 300064
Data recorded: 2022-11-25 09:40:16 GMT

Thank You!

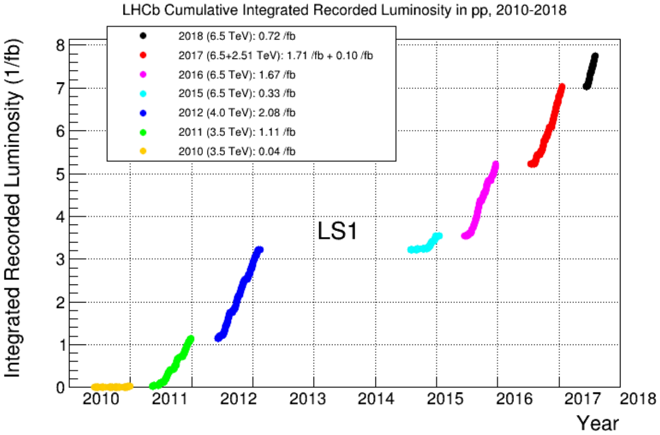
Backups

The LHCb experiment at the Large Hadron Collider

- The Large Hadron Collider (LHC) is a proton-proton accelerator
- LHCb is one of experiments based at the LHC at CERN, Geneva
- Forward spectrometer initially designed to search for New Physics in the beauty quark sector
- Now very broad programme: charm and top quark, heavy ions, electro-weak physics, Higgs physics, ...
- Excellent vertex resolution (PV resolution: $10 - 40\ \mu\text{m}$ in xy-plane and $50 - 300\ \mu\text{m}$ in z-axis)
- Impact parameter (IP) resolution around $12\ \mu\text{m}$ for high-momentum particles
- Momentum relative resolution of 0.5% below $20\,\text{GeV}/c$ and 0.8% around $100\,\text{GeV}/c$
- Typical PID efficiencies: $80\% - 95\%$ correct kaon ID and $3\% - 10\%$ misidentification of pion as kaon



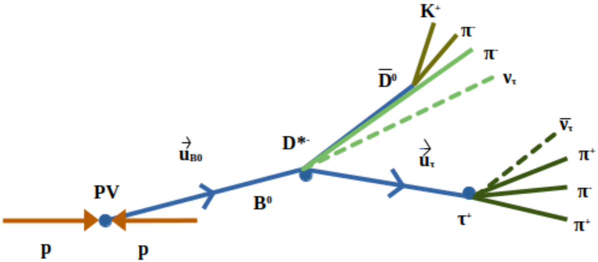
LHCb experiment

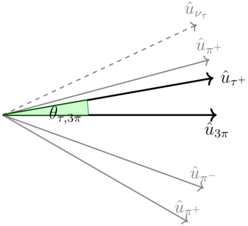


Period	$\int \mathcal{L}$	$\sqrt{s}$	**Number of** $b\bar{b}$
Run1 2011-2012	$3.2\,\text{fb}^{-1}$	7-8 TeV	2.5×10^{11}
Run2 2015-2016	$2.0\,\text{fb}^{-1}$	13 TeV	2.9×10^{11}
Run2 2017-2018	$3.9\,\text{fb}^{-1}$	13 TeV	5.7×10^{11}

$R(D^*)$ hadronic – Signal decay kinematics

- Neutrinos not detected; approximation needed for B reconstruction
- Well measured B^0 and τ^+ vertices allow reconstruction of flight directions
- Momentum as a function of angle between the systems





- Maximum allowed values for the angles $\Rightarrow$ unambiguous estimate of momentum

Two-fold ambiguities in determining τ momentum:

$$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}|\cos\theta_{\tau,3\pi} \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2\sin^2\theta_{\tau,3\pi}}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2\cos^2\theta_{\tau,3\pi})},$$

where $\theta_{\tau,3\pi}$ is the angle between the 3π system three-momentum and the τ line of flight. *Approximation:* take the maximum allowed angle

$$\theta_{\tau,3\pi} \approx \theta_{\tau,3\pi}^{\max} = \arcsin\left(\frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau|\vec{p}_{3\pi}|}\right),$$

The B^0 momentum is obtained similarly:

$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2|\vec{p}_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2\cos^2\theta_{B^0,Y})}$$

with

$$\theta_{B^0,Y}^{\max} = \arcsin\left(\frac{m_{B^0}^2 - m_Y^2}{2m_{B^0}|\vec{p}_Y|}\right),$$

where Y represents the $D^{*-}\tau^+$ system.

Properties of charged leptons

Particle	Mass (MeV/c^2)	Lifetime	Main decay modes
e^-	0.5109989461(31)	>6.6×10^{26} years	–
μ^-	105.6583745(24)	2.1969811(22) μs	$e^-\bar{\nu}_e\nu_\mu$
τ^-	1776.86(12)	290.3(5) fs	$\pi^-\pi^0\nu_\tau$ (25.5%) $e^-\bar{\nu}_e\nu_\tau$ (17.8%) $\mu^-\bar{\nu}_\mu\nu_\tau$ (17.39%) $\pi^-\nu_\tau$ (10.8%) $\pi^-\pi^+\pi^-\nu_\tau$ (9.3%)

τ lepton Branching Ratios [PDG 2018]

Mode	$\mathcal{BR}$ (%)
$\tau^- \to \pi^-\pi^0\nu_\tau$	25.49 ± 0.09
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$	17.82 ± 0.04
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	17.39 ± 0.04
$\tau^- \to \pi^-\nu_\tau$	10.82 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$	9.31 ± 0.05
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$	4.62 ± 0.05

D^* branching ratios

Mode	$\mathcal{BR}$
$D^*(2007)^0 \rightarrow D^0\pi^0$	$(64.7 \pm 0.9)\%$
$D^*(2007)^0 \rightarrow D^0\gamma$	$(35.3 \pm 0.9)\%$
$D^*(2010)^+ \rightarrow D^0\pi^+$	$(67.7 \pm 0.5)\%$
$D^*(2010)^+ \rightarrow D^+\pi^0$	$(30.7 \pm 0.5)\%$
$D^*(2010)^+ \rightarrow D^+\gamma$	$(1.6 \pm 0.4)\%$

Particle	Mass (MeV/c^2)	Lifetime
D^+	1869.65 ± 0.05	(1.040 ± 0.007) ps
D^0	1864.83 ± 0.05	(0.4101 ± 0.0015) ps
D_s^+	1968.34 ± 0.07	(0.504 ± 0.004) ps
Λ_c^+	2286.46 ± 0.14	(0.200 ± 0.006) ps
$D^*(2007)^0$	2006.85 ± 0.05	–
$D^*(2010)^-$	2010.26 ± 26	–

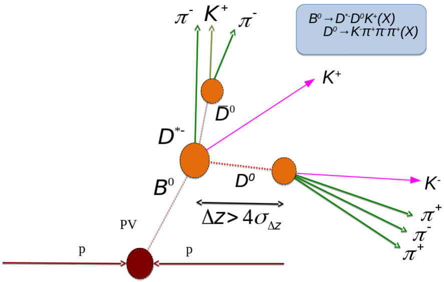
Relevant branching ratios

Mode	$\mathcal{BR}$
$B^0 \to D^*(2010)^- D_s^+$	$(8.0 \pm 1.1) \times 10^{-3}$
$B^0 \to D^*(2010)^- D_s^{*+}$	$(1.77 \pm 0.14) \times 10^{-2}$
$B^0 \to D^*(2010)^- D^0 K^+$	$(2.47 \pm 0.10 \pm 0.18) \times 10^{-3}$
$B^0 \to D^*(2010)^- D^*(2007) K^+$	$(10.6 \pm 0.33 \pm 0.86) \times 10^{-3}$
$B^0 \to D^*(2010)^- \pi^+ \pi^+ \pi^- \pi^0$	$(1.67 \pm 0.27)\%$
$B^0 \to D^*(2010)^- 3\pi^+ \pi^+ 2\pi^-$	$(4.7 \pm 0.9)\%$
$B^0 \to D^*(2010)^- D_{s0}(2317)^+$	$(1.5 \pm 0.6)\%$
$B^0 \to D^*(2010)^- D_{sJ}(2457)^+$	$(9.3 \pm 2.2) \times 10^{-3}$
$B^0 \to D^*(2010)^- D_{s1}(2536)^+,\ D_{s1}^+ \to D^{*0} K^+ + D^{*+} K^0$	$(5.0 \pm 1.4) \times 10^{-3}$

$R(D^*)$ hadronic – Double-charm backgrounds

- $B \to D^{*-}(D^+, D^0)X$ decays are sub-leading contributors
- $D^+ \to K^-\pi^+\pi^+(\pi^0)$ contributes to the $B \to D^{*-}D^+X$ backgrounds
  - Significant when π^- is misidentified as K^-
  - Tight particle identification requirements

- $D^0 \to K^-3\pi^\pm$ contributes to the $B \to D^{*-}D^0X$ backgrounds
  - When there is an extra charged track
  - A BDT classifier is used to reject such events



$R(D^*)$ hadronic – Double-charm backgrounds

- Double-charm decays being the largest fraction in the final sample, need to be modelled well in the final signal extraction fit
  - Templates used in the signal fit are derived from simulation and corrections need to be applied wherever necessary
- Specific control samples derived using the peculiarities of these decays for further studies

Decay	**Sample selection**
$B \to D^{*-} D_s^+ X$	reversing the anti-D_s^+ BDT selection
$B \to D^{*-} D_s^+ (\to 3\pi^\pm) X$	$m(3\pi^\pm)$ around D_s^+ mass
$B \to D^{*-} D^+ X$	kaon mass hypothesis given to π^- among the $3\pi^\pm$ candidates
$B \to D^{*-} D^0 X$	additional charged track (kaon) selected in an event

$R(D^*)$ hadronic – Normalisation & signal selection

- Remaining cuts for the *normalisation* mode

Variable	cut	targeted background
$m(B^0)$	$\in [5150, 5400]$ MeV	combinatorial
$m(D^{*-}) - m(\bar{D}^0)$	$\in [143, 148]$ MeV$/c^2$	combinatorial D^{*-}
$m(K^-\pi^+)$	$\in [1840, 1890]$ MeV$/c^2$	combinatorial D^0
$[\text{vtx}_z(\bar{D}^0) - \text{vtx}_z(\tau^+)]/\text{error}$	> 4	non-prompt
ProbNNpi π^- from D^{*-}	> 0.1	misidentification
ProbNNpi $\pi^\pm$ from τ^+	> 0.6	misidentification
ProbNNk π^- from τ^+	< 0.1	misidentification
isolation BDT	> 0.1	double-charm
combinatorial BDTD	> 0.0	combinatorial

$R(D^*)$ hadronic – Normalisation & signalselection

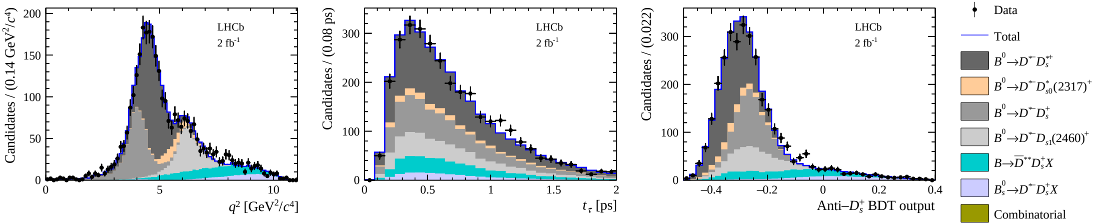
- Remaining cuts for the *signal* mode

Variable	cut	background targeted
$[\text{vtx}_z(\tau^+) - \text{vtx}_z(B^0)]/\text{error}$	> 2	prompt
$m(K^-\pi^+)$	$\in [1840, 1890]\ \text{MeV}/c^2$	combinatorial D^0
$m(D^{*-}) - m(K^-\pi^+)$	$\in [143, 148]\ \text{MeV}/c^2$	combinatorial D^{*-}
$m(\tau^+)$	$< 1600\ \text{MeV}/c^2$	double-charm
$m(B^0)$	$< 5100\ \text{MeV}/c^2$	combinatorial
q^2	$\in [0, 11]\ \text{GeV}^2/c^4$	combinatorial
ProbNNpi π^- from D^{*-}	> 0.1	misidentification
ProbNNpi $\pi^\pm$ from τ^+	> 0.6	misidentification
ProbNNk π^- from τ^+	< 0.1	misidentification
anti D_s^+ BDT	> -0.2	$D^{*-} D_s^+ X$
isolation BDT	> 0.0	double-charm
combinatorial BDTD	> 0.0	combinatorial
detachment BDTG	> 0.2	prompt

$R(D^*)$ hadronic – Production of D_s^+ in $B \to D^{*-} D_s^+ X$

- $B \to D^{*-} D_s^+ X$ decays produced in a spectrum of $B \to D^{*-} D_s^{+(*,**)} X$ processes
- Rare knowledge about the fraction of each process
- Enriched data sample of double charm decays with fully reconstructed $D_s^+ \to 3\pi^{\pm}$ process
- Fit to $m(D^{*-}3\pi)$

$$\mathcal{P} = f_{\text{c.b.}} \mathcal{P}_{\text{c.b.}} + \frac{(1 - f_{\text{c.b.}})}{k} \sum_i f_i \mathcal{P}_i,$$



- Fractions of each component determined and used as constraints in the signal extraction fit
- Projections of data and simulations on the fit variables shows a good agreement

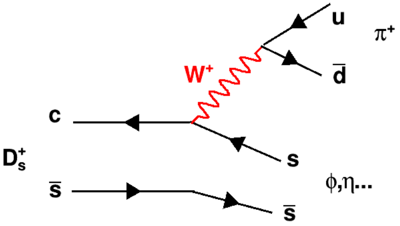
$R(D^*)$ hadronic – Decays of D_s^+ in $B \to D^{*-} D_s^+ X$

- Data sample selected with low anti-D_s^+ BDT score
- Simultaneous fit to $m(\pi^+\pi^-)_{\text{min}}$, $m(\pi^+\pi^-)_{\text{max}}$, $m(\pi^+\pi^+)$ and $m(3\pi^\pm)$
- The fit model PDF is constructed as

$$\mathcal{P}_{\text{total}} = N_{D_s^+} \sum_i f_i \mathcal{P}_i(D_s^+) + N_{non-D_s^+} \mathcal{P}_{non-D_s^+}$$

where i represents different D_s^+ decay modes

- The different D_s^+ modes can be broadly divided into
    - $\eta\pi^+/\eta\rho^+$
    - $\eta'\pi^+/\eta'\rho^+$
    - $(\omega+\phi)\pi^+/(\omega+\phi)\rho^+$
    - rest of the modes - $\eta 3\pi$, ηa_1, $\eta' 3\pi$, $\eta' a_1$, $\omega 3\pi$, ωa_1,$\phi 3\pi$, ϕa_1, $K^0 3\pi$, $K^0 a_1$, $\tau\nu$ and non-resonant 3π



$R(D^*)$ hadronic – Signal fit extraction – PDF

The signal yield is determined from a 3-dimensional maximum likelihood binned fit to q^2 (8 bins), decay time of the τ^+-candidate (8 bins), t_τ, and the anti-D_s^+ BDT (6 bins).

- The total probability density function is:

$$
\begin{aligned}
\mathcal{P}_{\text{total}}(q^2, t_\tau, \text{BDT}) = 1/N_{\text{total}} \times \{ & N_{\text{sig}} \left[f_{\tau^+\to\pi^+\pi^-\pi^+\overline{\nu}_\tau} \ \mathcal{P}_{\tau^+\to\pi^+\pi^-\pi^+\overline{\nu}_\tau} + (1 - \ f_{\tau^+\to\pi^+\pi^-\pi^+\overline{\nu}_\tau} \ ) \mathcal{P}_{\tau^+\to\pi^+\pi^-\pi^+\pi^0\overline{\nu}_\tau} \right. \\
& + f_{D^{**}\tau\nu} \ \mathcal{P}_{B\to D^{**}\tau^+\nu_\tau} \ ] + N_{D^0}^{\text{same}} \ [\mathcal{P}_{B\to D^{*-}D^0X \text{ SV}} + f_{D^0}^{v_1-v_2} \ \mathcal{P}_{B\to D^{*-}D^0X \text{ DV}} \ ] \\
& + N_{D_s^+} \ /k \times [\mathcal{P}_{B^0\to D^{*-}D_s^{*+}} + f_{D_s^+} \ \mathcal{P}_{B^0\to D^{*-}D_s^+} + f_{D_{s0}^{*+}} \ \mathcal{P}_{B^0\to D^{*-}D_{s0}^{*+}} \\
& + f_{D_{s1}^+} \ \mathcal{P}_{B^0\to D^{*-}D_{s1}^+} + f_{D^{**}D_sX} \ \mathcal{P}_{B\to D^{**-}D_s^+X} + f_{B_s\to D^*D_s^+X} \ \mathcal{P}_{B_s^0\to D^{*-}D_s^+X} \ ] \\
& + N_{D_s^+} \ f_{D^+} \ \mathcal{P}_{B\to D^{*-}D^+X} + N_{B\to D^{*-}3\pi^\pm X} \ \mathcal{P}_{B\to D^{*-}3\pi^\pm X} \\
& + N_{B_1-B_2} \ \mathcal{P}_{\text{combinatoric } B} + N_{\text{fake } D^0} \ \mathcal{P}_{\text{combinatoric } D^0} + N_{\text{fake } D^*} \ \mathcal{P}_{\text{combinatoric } D^{*-}} \ \}
\end{aligned}
$$

- 16 templates: 13 templates from simulation, 3 templates from data
- 4 free parameters, 6 gaussian constrained parameters and 6 fixed parameters

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& + f_{D^{**}\tau\nu} \mathcal{P}_{B\to D^{**}\tau^+\nu_\tau}] + N_{D^0}^{\text{same}} [\mathcal{P}_{B\to D^{*-}D^0 X\ \text{SV}} + f_{D^0}^{v_1-v_2} \mathcal{P}_{B\to D^{*-}D^0 X\ \text{DV}}] \\
& + N_{D_s^+}/k \times [\mathcal{P}_{B^0\to D^{*-}D_s^{*+}} + f_{D_s^+} \mathcal{P}_{B^0\to D^{*-}D_s^+} + f_{D_{s0}^{*+}} \mathcal{P}_{B^0\to D^{*-}D_{s0}^{*+}} \\
& + f_{D_{s1}^+} \mathcal{P}_{B^0\to D^{*-}D_{s1}^+} + f_{D^{**}D_s X} \mathcal{P}_{B\to D^{**-}D_s^+ X} + f_{B_s\to D^* D_s^+ X} \mathcal{P}_{B_s^0\to D^{*-}D_s^+ X}] \\
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& + N_{B_1-B_2} \mathcal{P}_{\text{combinatoric } B} + N_{\text{fake } D^0} \mathcal{P}_{\text{combinatoric } D^0} + N_{\text{fake } D^*} \mathcal{P}_{\text{combinatoric } D^{*-}} \}
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Future of $R(X_c)$ at LHCb