Lepton Flavor Universality test using $B \to D^* \tau \nu$ decays at LHCb

CPPM Seminar

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30th October, 2023

Outline

Introduction

LHCb

$R(D^*)$ with hadronic τ decays

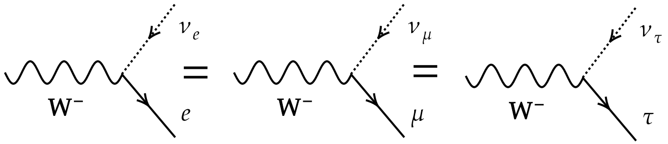
Current status and prospects

Conclusions

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)

To test the LFU, we measure a ratio of branching fractions $\mathcal{B}$ because:

- Reduces theoretical uncertainties
- New physics may be more sensible to the 3rd family

- 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

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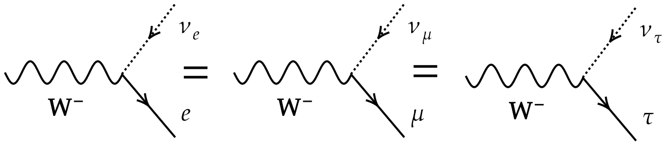

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Published results (LHCb)

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

- $R(D^*)$ (Run 1 and partial Run 2 data) [PRD **108**, 012018 (2023)]
- $R(\Lambda_c)$ (Run 1 data) [PRL **128**, 191803 (2022)]

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

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- $R(J/\psi)$ (Run 1 data) [PRL **120**, 121801 (2018)]
- $R(D)$–$R(D^*)$ (Run 1 data) [PRL **131**, 111802 (2023)]

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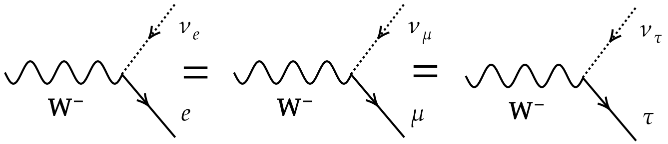

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today's topic

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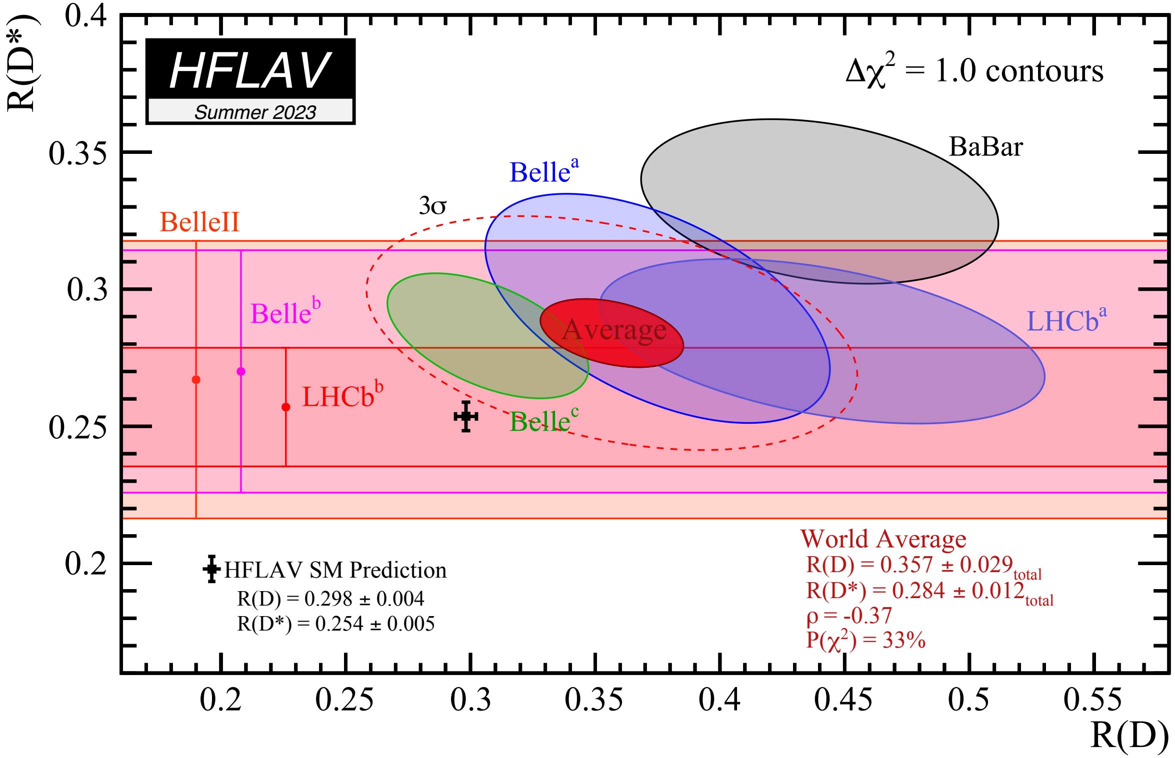
$R(D)$–$R(D^*)$ results



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

- The world average becomes

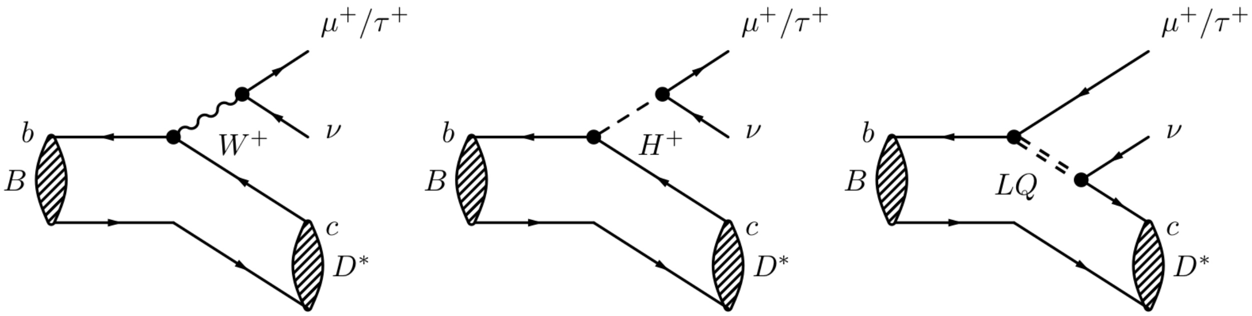
$$\begin{cases} R(D^*) & = 0.284 \pm 0.012 \\ R(D) & = 0.357 \pm 0.029 \end{cases}$$

- The deviation w.r.t. the SM is at **3.3σ** for the combination of $R(D)$–$R(D^*)$

[HFLAV]

What could be behind LFU violation?

SM | Charged Higgs | Leptoquark

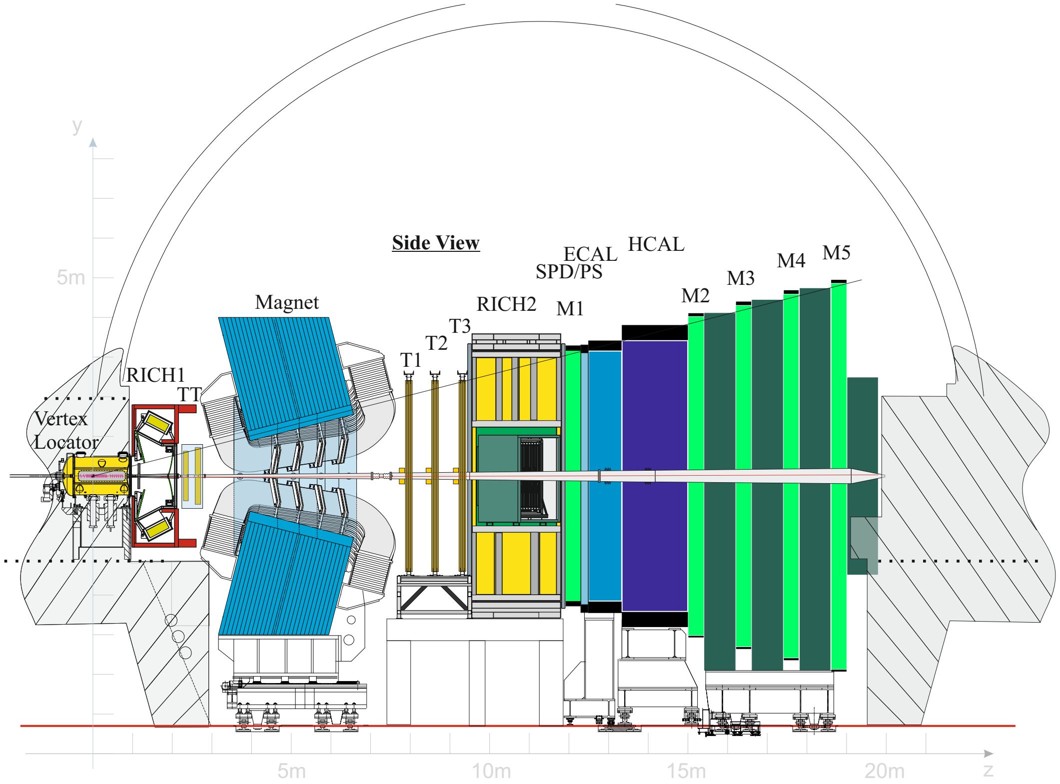


There are three typical candidates to account for the $R(D)$ and $R(D^*)$ anomalies:

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

LHCb

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)]

$R(D^*)$ with hadronic τ decays

Plan:

- Methodology
- $R(D^*)$ partial Run 2 [PRD **108**, 012018 (2023)]
  - Cross-checks
  - Systematics
- $R(D^*)$ full Run 2 (ongoing)

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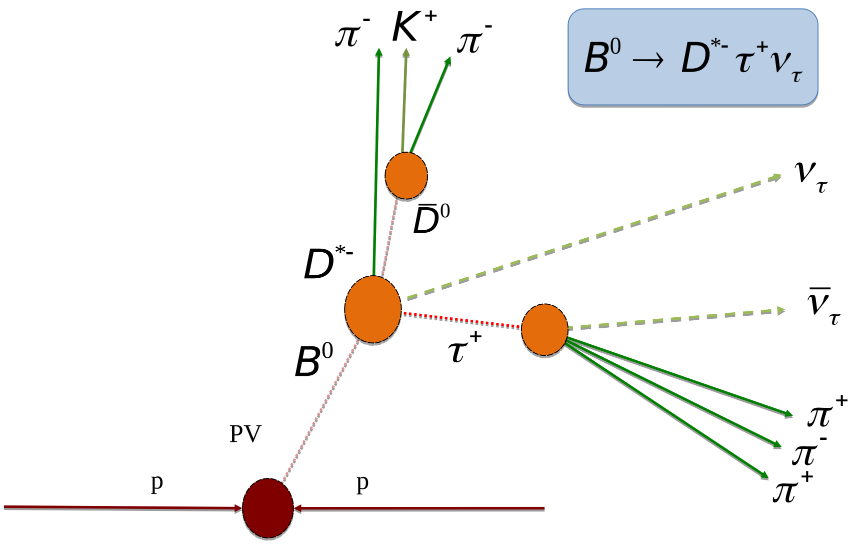
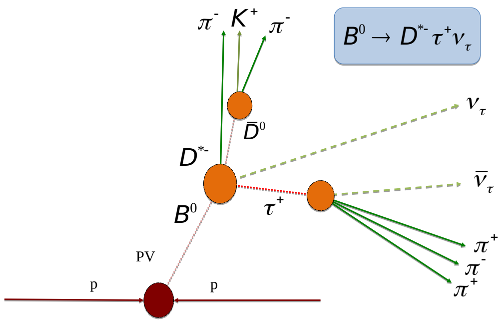


Common properties:

- Neutrinos in the final state $\Longrightarrow$ No peaking signal region
  - Need MC templates to extract the signal yield
  - Approximation to reconstruct B and τ momentum
- Introduce *normalisation* mode with same visible final states
  - $\Longrightarrow$ External inputs to measure $R(D^*)$

Signal & Normalisation mode

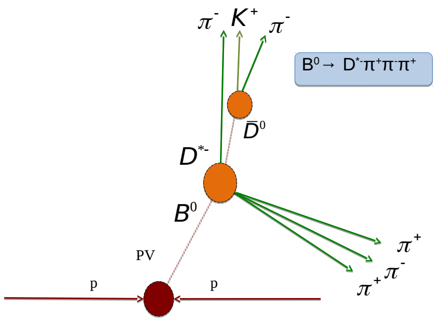
Signal mode



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

- 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

[PRD **108**, 012018 (2023)]

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:

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

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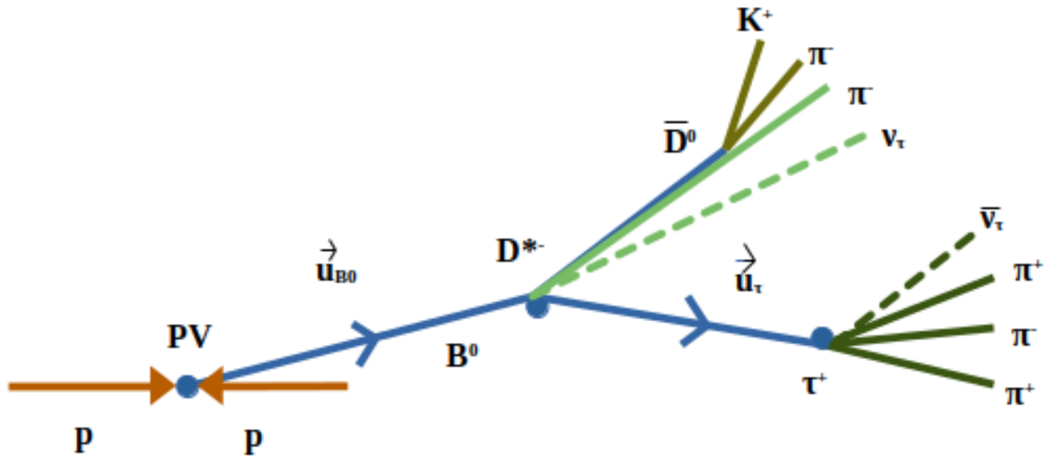
- $\mathcal{N}_{\mathtt{sig}}$ from a 3D binned template fit:
  - $q^2 = (p_B - p_{D^*})^2$ momemtum transfered to the leptonic system (8 bins),
  - τ^+ lifetime t_τ (8 bins),
  - Anti-D_s^+ BDT (6 bins).
- $\mathcal{N}_{\mathrm{norm}}$ from an unbinned fit to $m(D^*3\pi^\pm)$
- Efficiencies $\varepsilon_{\mathrm{sig}}$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

[PRD **108**, 012018 (2023)]

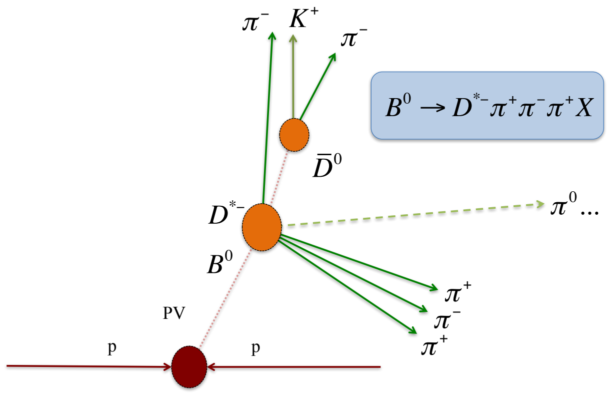
Signal decay kinematics

- Signal mode with 2 (missing) neutrinos in the final state
- Approximation needed for τ and B reconstruction



- Momentum and Energy conservation
- Well measured B^0 and τ^+ vertices (allow reconstruction of flight directions)
- $\implies$ Determination of p_B and p_τ

Dominant backgrounds



Prompt backgrounds

- 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

[PRD **108**, 012018 (2023)]

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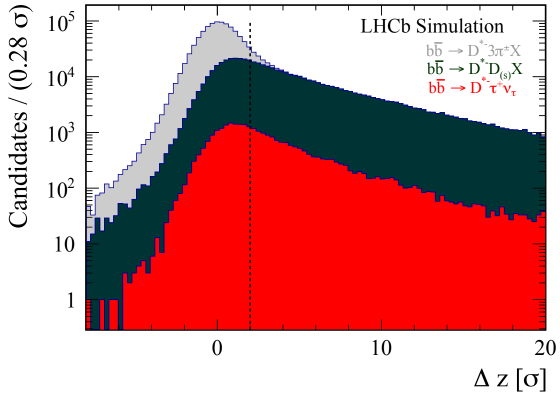

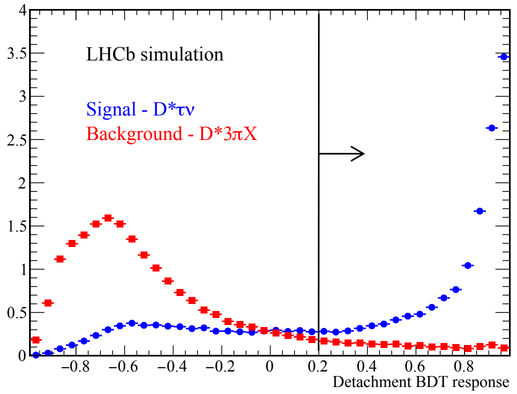

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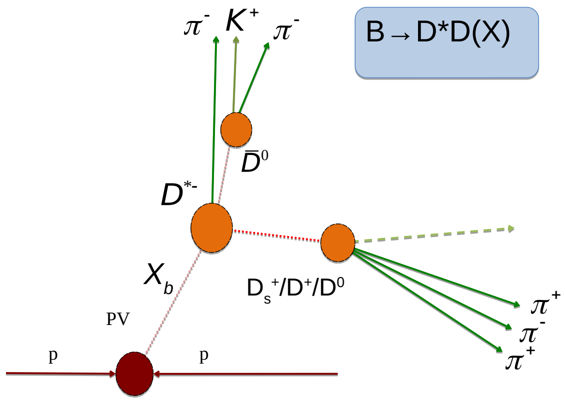
Selection criteria

- 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 %**

[PRD **108**, 012018 (2023)]

Dominant backgrounds



Double charm backgrounds

- The second largest contribution from double charm decays $B \to D^{*-}DX$
  - $D = D_s^+, D^+, D^0$
  - Signal like topology with a detached vertex due to non-negligible lifetime
  - $B \to D^{*-}D_s^+X \sim 10\times$ signal decays
  - $B \to D^{*-}D^+X \sim 1\times$ signal decays
  - $B \to D^{*-}D^0X \sim 0.2\times$ signal decays

[PRD **108**, 012018 (2023)]

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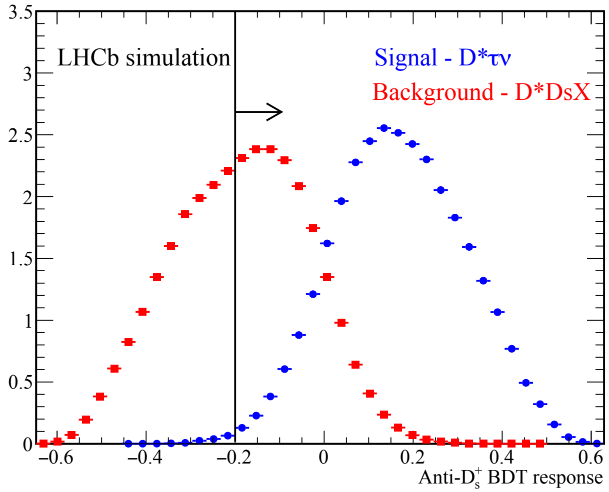

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Selection criteria

- 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

[PRD **108**, 012018 (2023)]

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
- Limited knowledge on the fraction of each process

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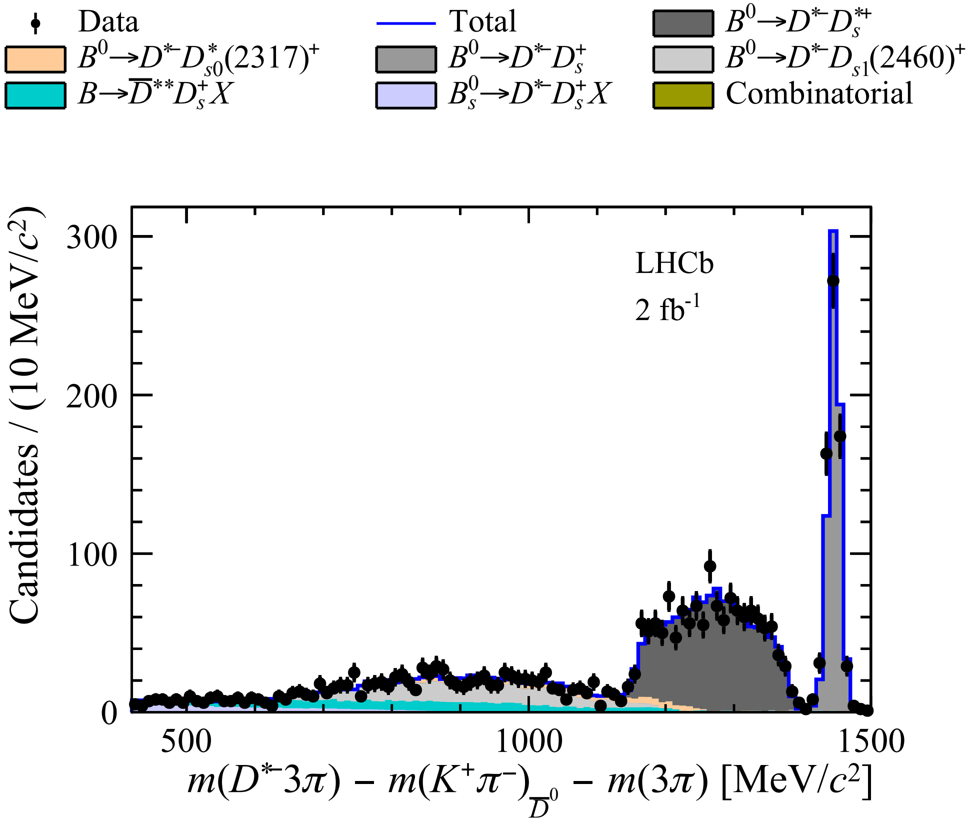
- Enriched data sample of double charm decays with fully reconstructed $D_s^+ \to 3\pi^\pm$ process
- Fit to $m(D^{*-} 3\pi)$



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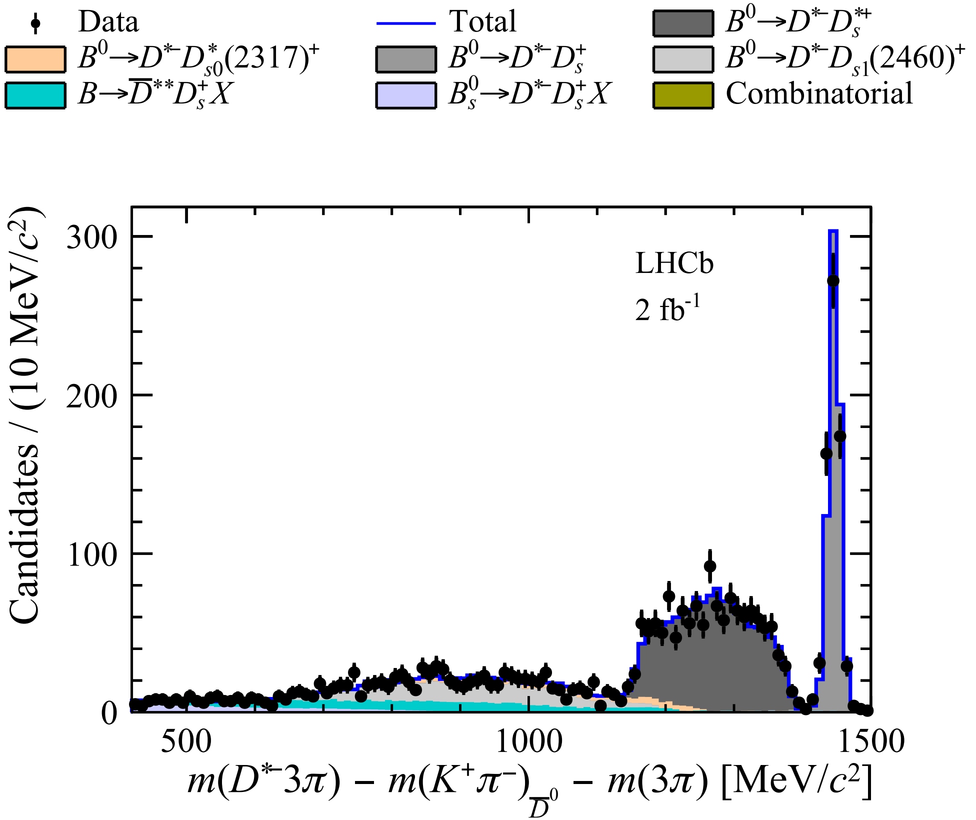
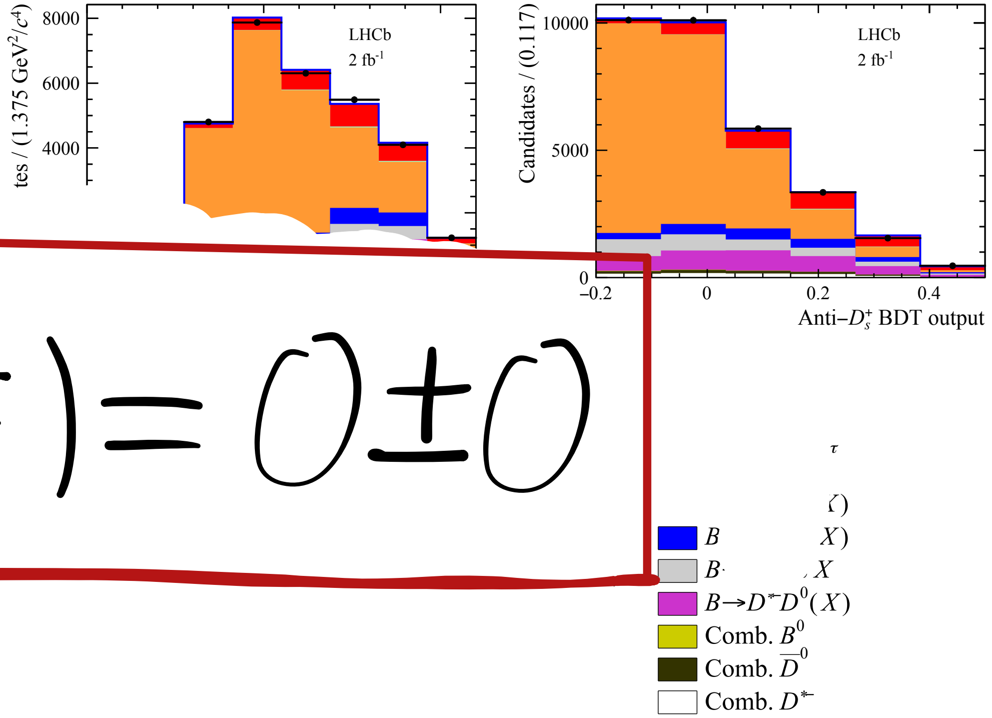
- Fit to $m(D^{*-} 3\pi)$
- Fractions of each component determined and used as constraints in the signal extraction fit
- Projections of data and simulations on the fit variables shows a good agreement



[PRD **108**, 012018 (2023)]

Signal fit

[PRD **108**, 012018 (2023)]



$N(B \to D^{*} \tau \mu t) = 0 \pm 0$

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

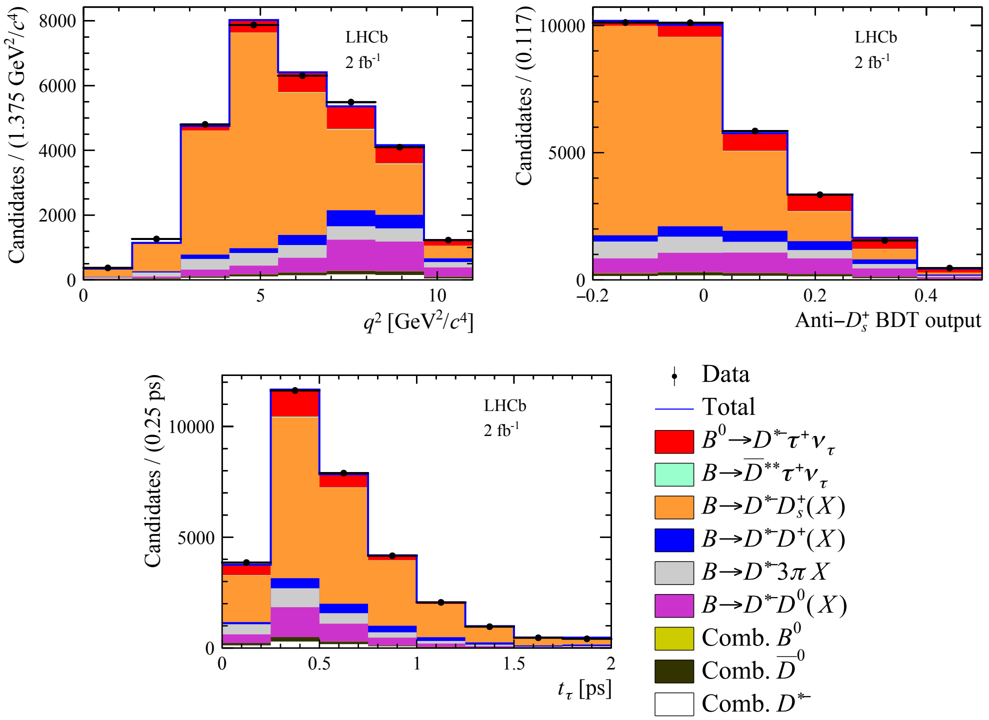
Signal fit

[PRD **108**, 012018 (2023)]

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

$$\mathcal{N}_{\texttt{sig}} = \mathbf{2469 \pm 154}$$

(Run 1: $\mathcal{N}_{\texttt{sig}} = 1296 \pm 86$)



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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

[PRD **108**, 012018 (2023)]

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

Final result

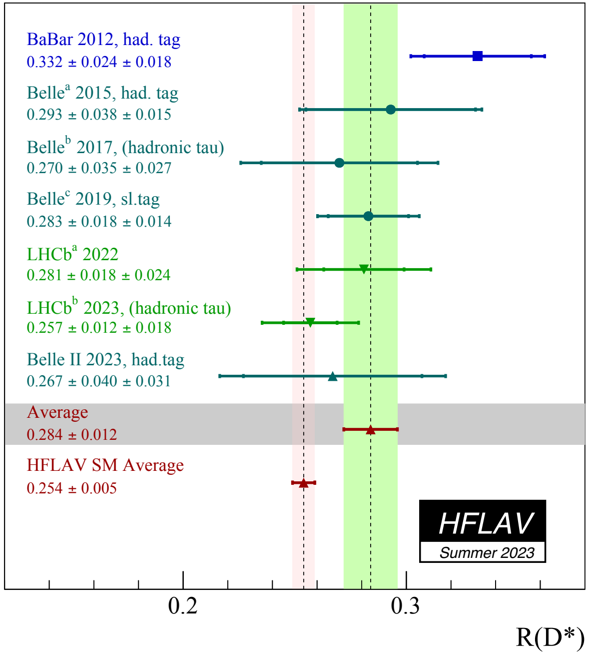
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

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

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



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

[HFLAV]

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

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

[PRD **108**, 012018 (2023)]

Current status and prospects

Main improvements in this analylsis

Hadronic $R(D^*)$ using Run 2

More statistics:

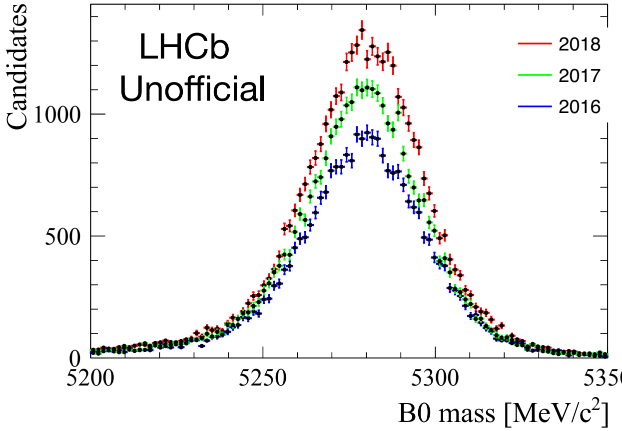
- Expected statistical uncertainty of the order of 3% for run 1 and run 2
  (while: 6.7% for run 1 only and for 5% run 1 + partial run 2)

Modeling of $B \to D^{*-} D_s^+(X)$ backgrounds:

- New MC samples with improved Ds decay model were requested and produced.
- We improved the description of numerous D_s^+ decays related to this analysis according to the recent BESIII result (arXiv:2212.13072)
  - Correct branching fractions
  - Add new decay channels

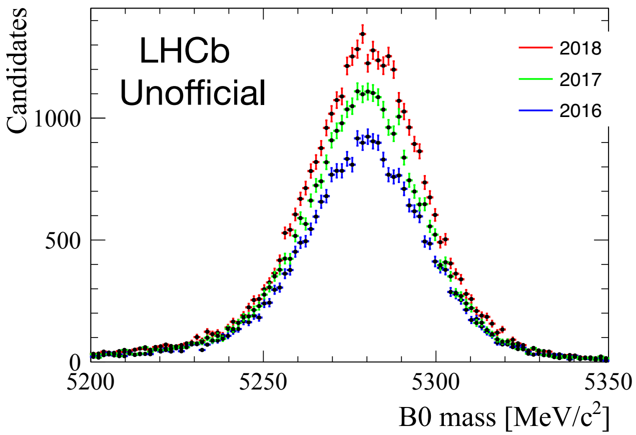
Current status & prospect

- Cut based selection
- Efficiencies of signal and normalisation modes
- Control samples, extract parameters and fractions
- Signal and normalisation fits
- Systematic uncertainties



Current status & prospect

- Cut based selection Completed
- Efficiencies of signal and normalisation modes Completed
- Control samples, extract parameters and fractions Ongoing
- Signal and normalisation fits todo
- Systematic uncertainties todo



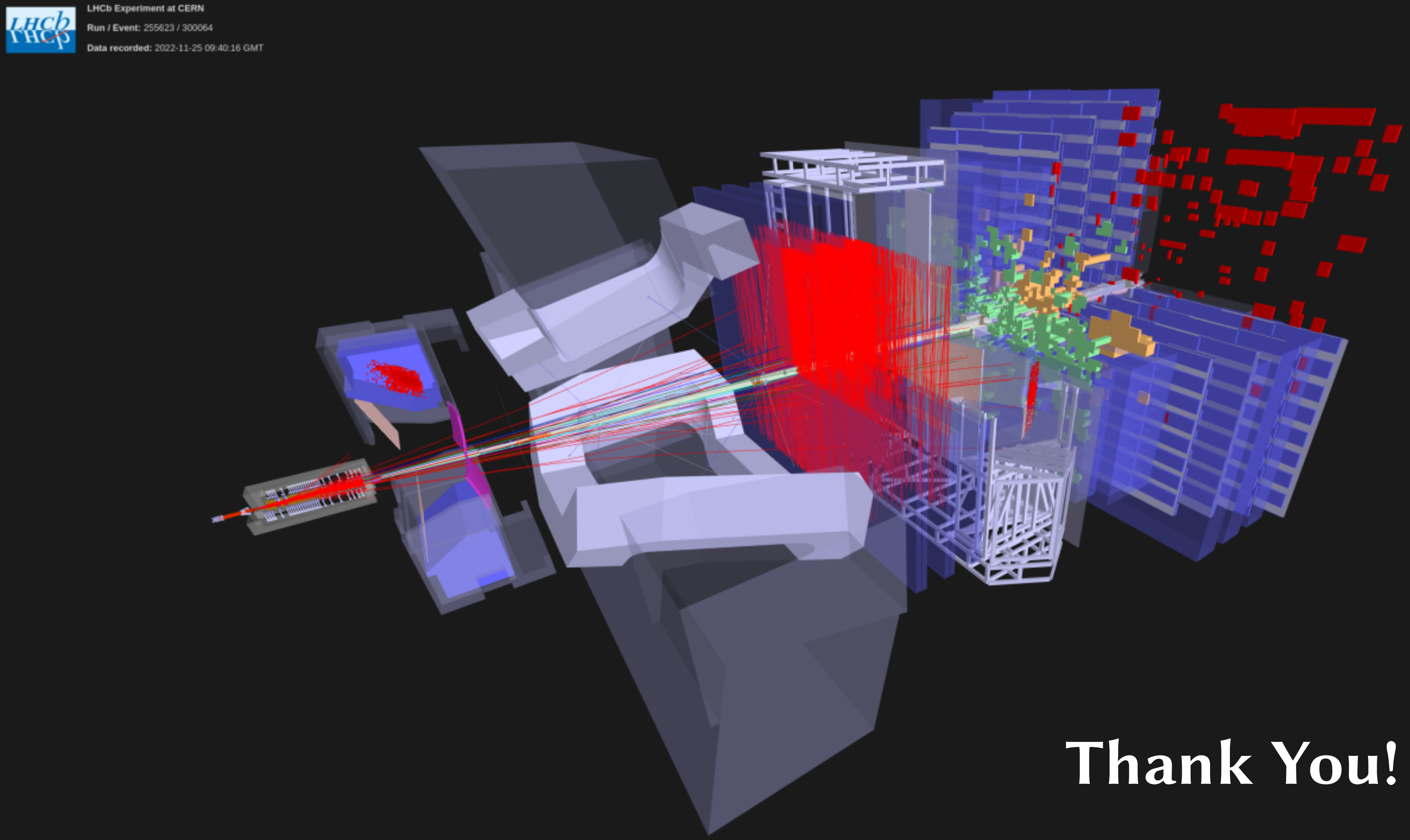
Conclusions

Conclusions

- The combined $R(D)$–$R(D^*)$ is still at 3.3σ tension from the SM

- $R(D^*)$ 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.

- Many more analyses to come: $R(D^0)$, $R(D^+)$, $R(D_s^+)$, $R(D^*)_{e/\tau}$ and *angular analysis* to determine spin structure of potential NP


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

Thank You!

Backups

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) Systematics

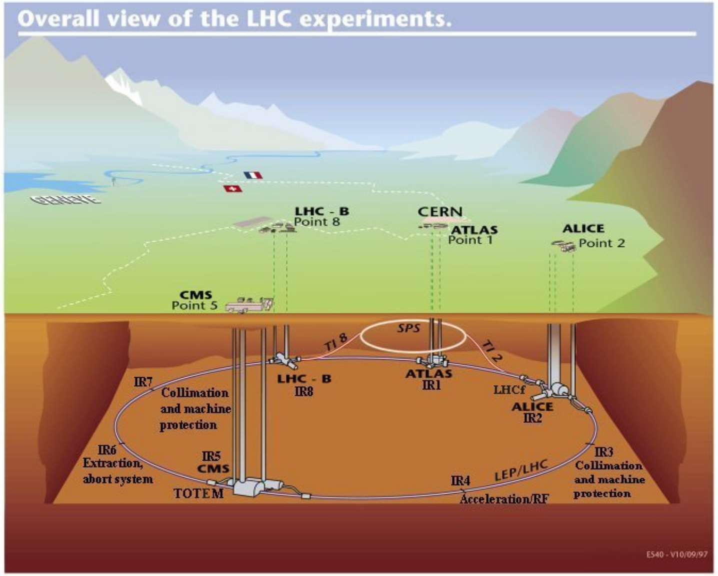
Breakdown of relative uncertainties:

Source	$R(D)/R(D^*)$ $\frac{\delta R(D^{*-})}{R(D^*)}$ [%]	Future
Simulated sample size	4.7	Produce more MC !
Empty bins in templates	1.3	
Signal decay model	1.8	
$D^{**}\ \tau\ \nu$ and $D_s^{**}\ \tau\ \nu$ feed-downs	2.7	Measure $R(D_1(2420)^0)$
$D_s^+ \to 3\pi X$ decay model	2.5	BESIII
$B \to D^{*-}D_s^+X,\ D^{*-}D^+X,\ D^{*-}D^0X$ bkgs	3.9	Improves with stat
Combinatorial background	0.7	
$B \to D^{*-}3\pi X$ background	2.8	Kill with $\lvert z\tau - zD\rvert > 5\sigma$
Efficiency ratio	3.9	Improves with stat
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0	
Total systematic uncertainty	9.1	
Statistical uncertainty	6.5	

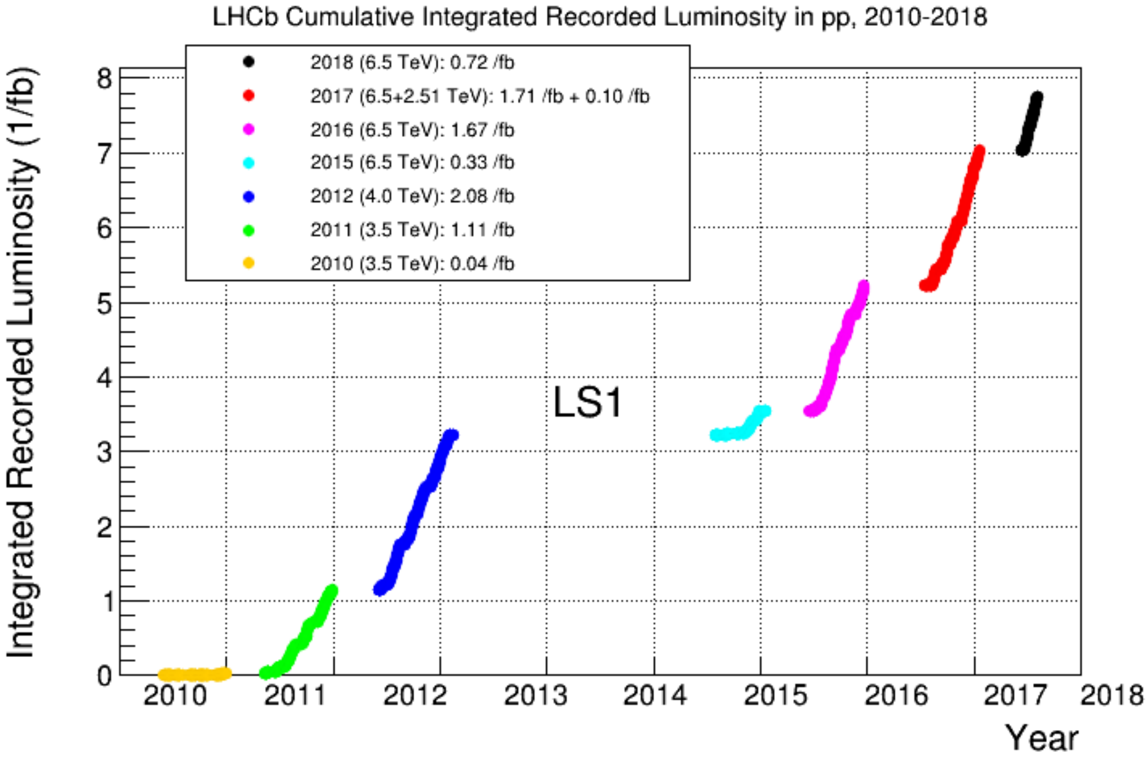
[PRL 120, 171802 2018]

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	$3.2\,\mathrm{fb}^{-1}$	7-8 TeV	2.5×10^{11}
Run2 2015-2016	$2.0\,\mathrm{fb}^{-1}$	13 TeV	2.9×10^{11}
Run2 2017-2018	$3.9\,\mathrm{fb}^{-1}$	13 TeV	5.7×10^{11}

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

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

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

The B^0 momentum is obtained similarly, with B^0 and $D^{*-}\tau^+$ instead of τ and 3π respectively.

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

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	–

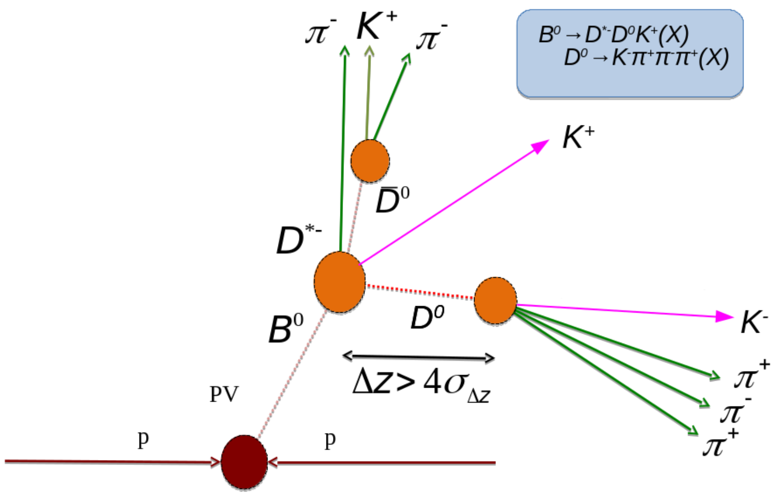
Relevant branching ratios

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
$m(D^{*-}) - m(\overline{D}^0)$	$\in [143, 148]$ MeV$/c^2$	combinatorial D^{*-}
$m(K^-\pi^+)$	$\in [1840, 1890]$ MeV$/c^2$	combinatorial D^0
$[\text{vtx}_z(\overline{D}^0) - \text{vtx}_z(\tau^+)]/\text{error}$	> 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
$[\mathrm{vtx}_z(\tau^+) - \mathrm{vtx}_z(B^0)]/\mathrm{error}$	> 2	prompt
$m(K^-\pi^+)$	$\in [1840, 1890]\,\mathrm{MeV}/c^2$	combinatorial D^0
$m(D^{*-}) - m(K^-\pi^+)$	$\in [143, 148]\,\mathrm{MeV}/c^2$	combinatorial D^{*-}
$m(\tau^+)$	$< 1600\,\mathrm{MeV}/c^2$	double-charm
$m(B^0)$	$< 5100\,\mathrm{MeV}/c^2$	combinatorial
q^2	$\in [0, 11]\,\mathrm{GeV}^2/c^4$	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

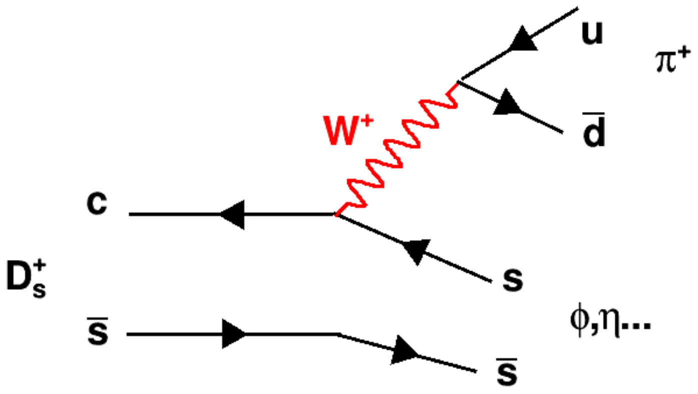
$R(D^*)$ hadronic – Decays of D_s^+ in $B \to D^{*-} D_s^+ X$

- 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

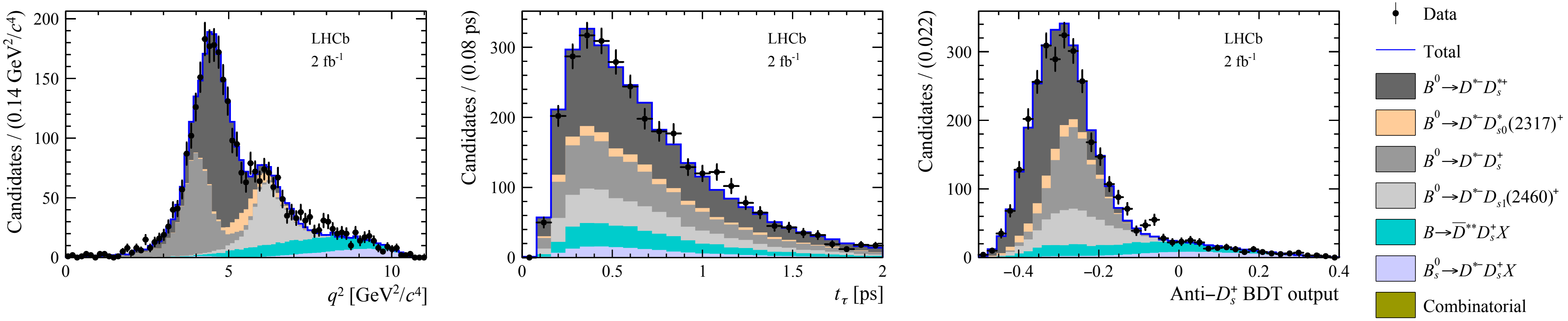
- The different D_s^+ modes can be broadly divided into
  - $\eta\pi^+/\eta\rho^+$
  - $\eta'\pi^+/\eta'\rho^+$
  - $(\omega+\phi)\pi^+/(\omega+\phi)\rho^+$
  - rest of the modes - $\eta 3\pi$, ηa_1, $\eta' 3\pi$, $\eta' a_1$, $\omega 3\pi$, ωa_1,$\phi 3\pi$, ϕa_1, $K^0 3\pi$, $K^0 a_1$, $\tau\nu$ and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



$R(D^*)$ hadronic – 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
- Limited 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 $m(D^{*-} 3\pi)$

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

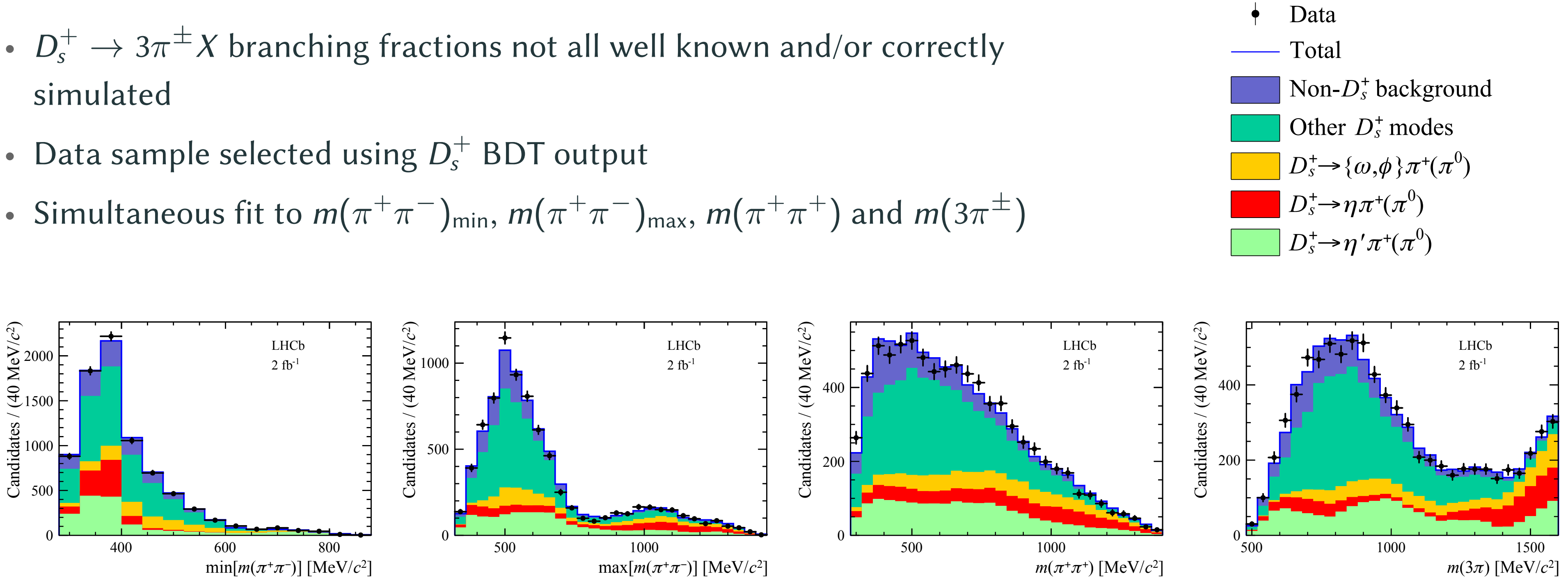


- Fractions of each component determined and used as constraints in the signal extraction fit
- Projections of data and simulations on the fit variables shows a good agreement

[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]

$R(D^*)$ 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:

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

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

$R(D^*)$ 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).

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$$
\begin{aligned}
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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^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}
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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} \,] \\
& + 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^{*-}} \, \}
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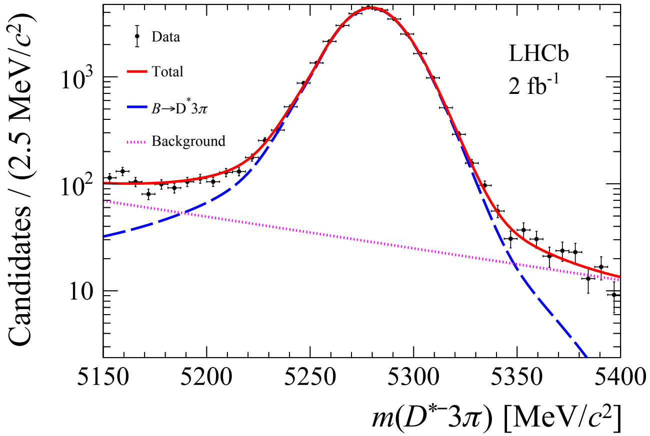
& + f_{D^{**}\tau\nu} \mathcal{P}_{B\to D^{**}\tau^+\nu_\tau}] + N^{\text{same}}_{D^0} [\mathcal{P}_{B\to D^{*-}D^0 X\ \text{SV}} + f^{v_1-v_2}_{D^0} \mathcal{P}_{B\to D^{*-}D^0 X\ \text{DV}}] \\
& + N_{D_s^+}/k \times [\mathcal{P}_{B^0\to D^{*-}D_s^{*+}} + f_{D_s^+} \mathcal{P}_{B^0\to D^{*-}D_s^+} + 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^0_s\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

Normalisation fit

- Unbinned maximum likelihood fit to $m(D^{*-}3\pi^{\pm})$
- Signal shape from simulation (CB and 2 gaussians)
  - Parameters of PDFs are fixed from simulation
- Fit in same data sample as signal
- Backgrounds:
  - $B^0 \to D^* D_s^+$ where $D_s^+ \to 3\pi^{\pm}$ (substracted $\sim$ 400 candidates)
  - Combinatorial background ($\to$ pink dashed line)
  - π MisId $B^0 \to D^* K\pi^+\pi^-$ negligible ($\mathcal{O}(10^{-4})$)

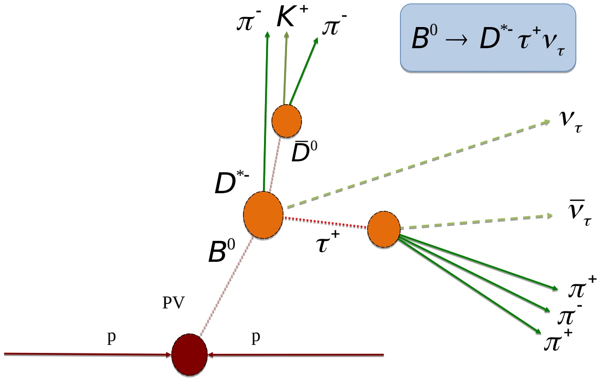


$\mathcal{N}_{\text{norm}} = \mathbf{30\ 540 \pm 182}$

[PRD **108**, 012018 (2023)]

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

Hadronic τ^+ decay



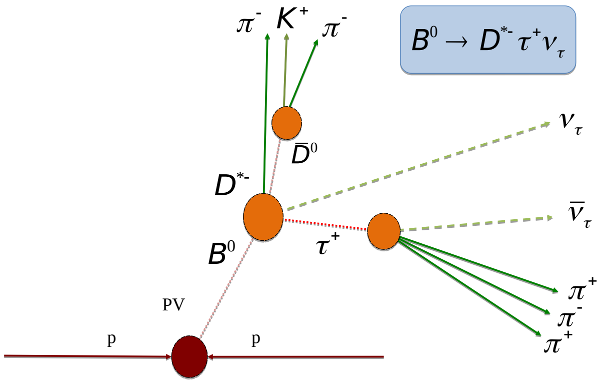
$\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- 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

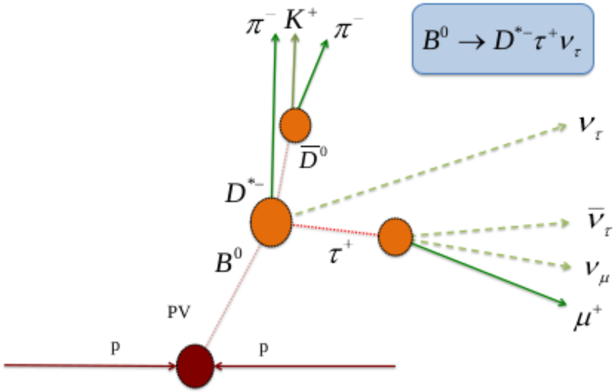


$\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

- 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]

Muonic τ^+ decay



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

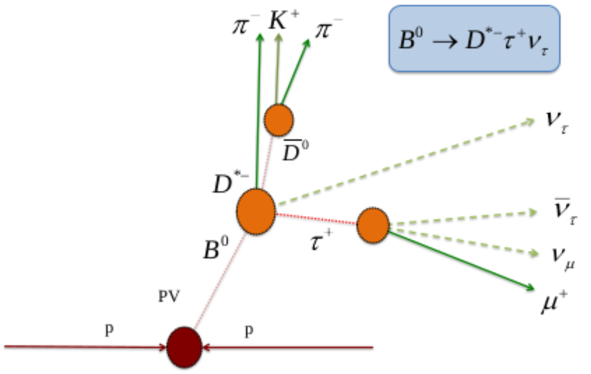
- **Direct measurement of** $R(X_c)$
- **High statistics**
- Backgrounds from D^+ must be controlled well
- Sensitive to $D^{**}\mu^-\nu_\mu$

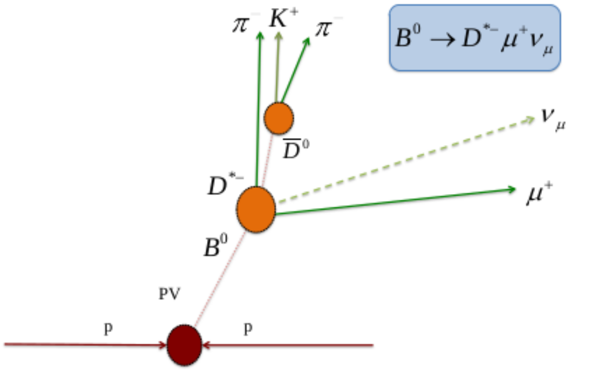
[arXiv:2302.02886]

$R(D)$–$R(D^*)$ with muonic τ decays

[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





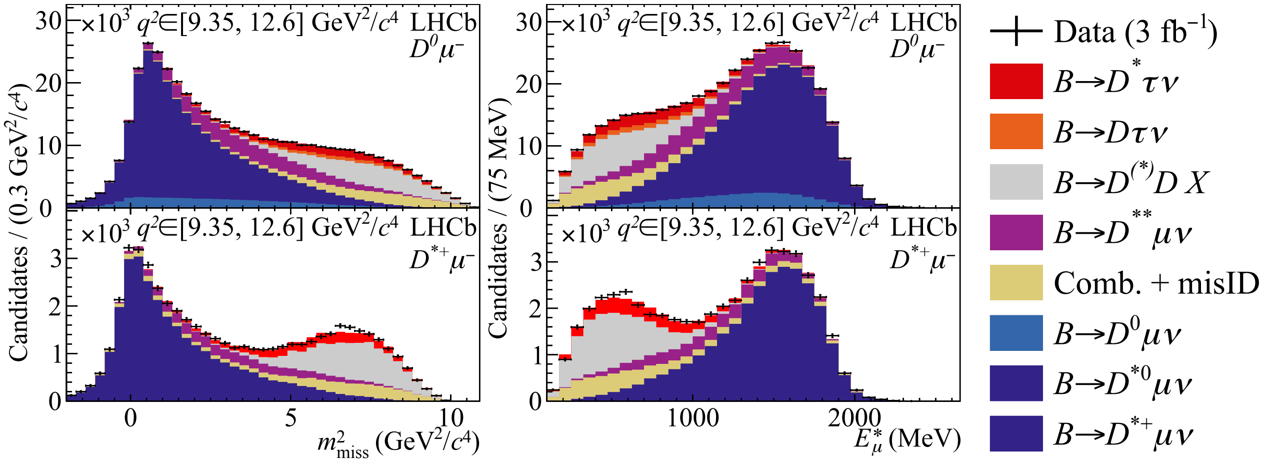
$R(D)$–$R(D^*)$ with muonic τ decays

[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

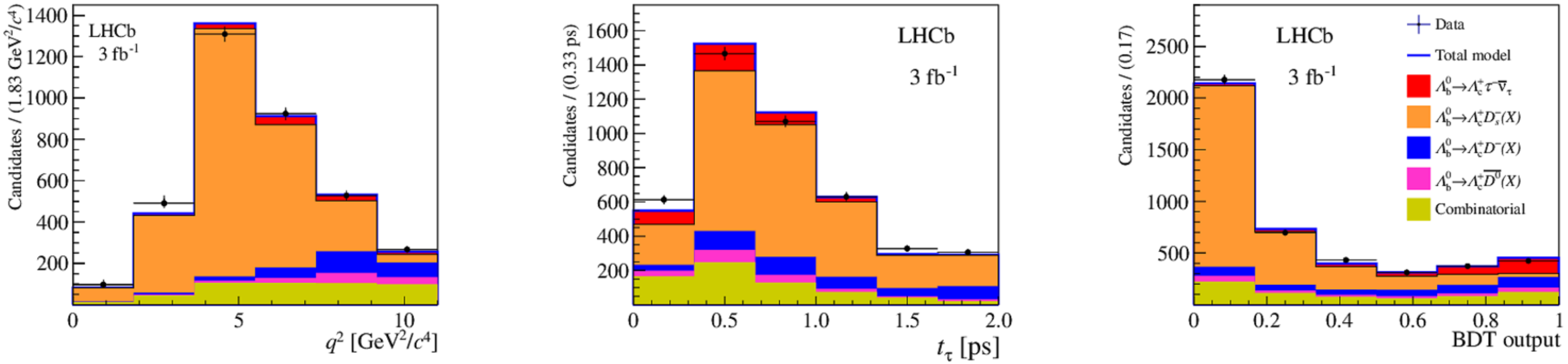
$R(\Lambda_c)$ with hadronic τ decays

- 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



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

$R(\Lambda_c)$ with hadronic τ decays

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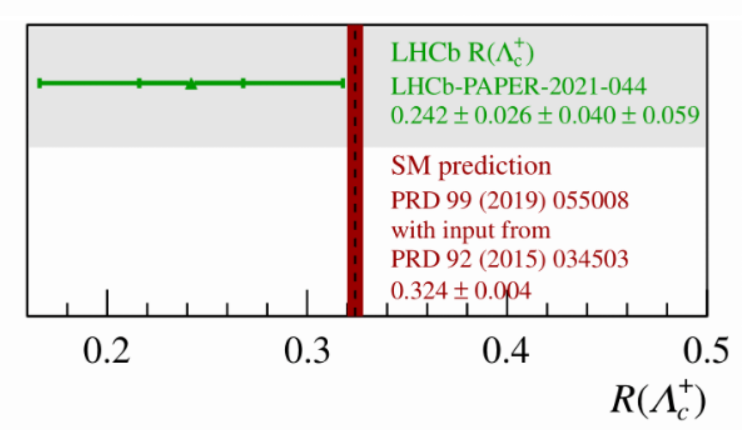
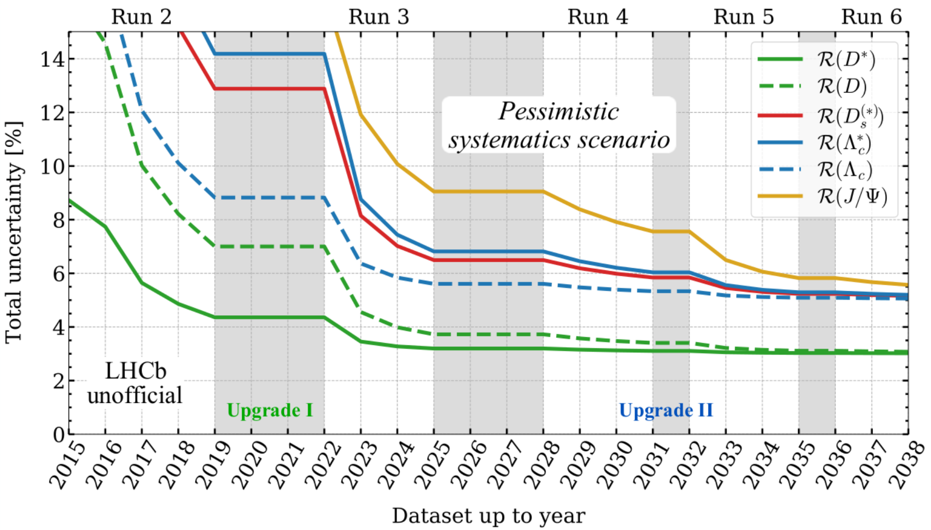


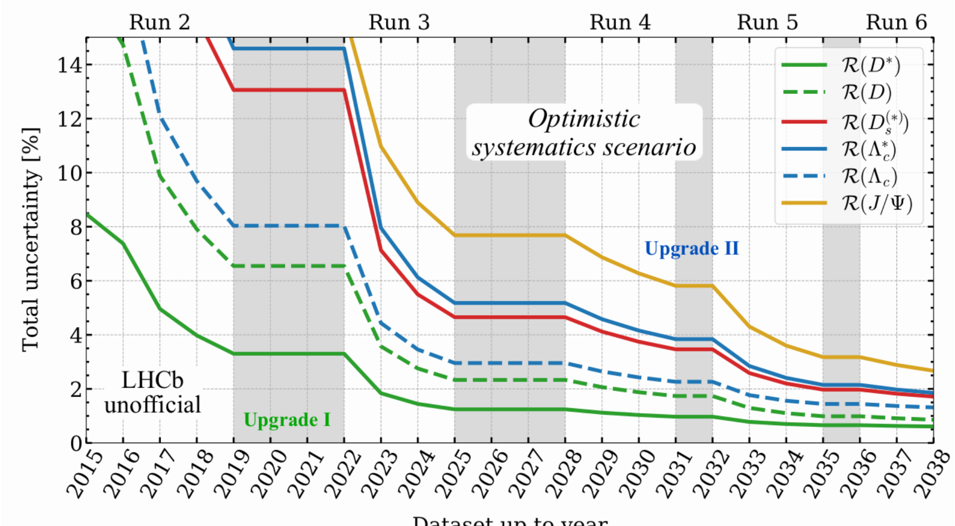
$$\begin{cases} \mathcal{K}(\Lambda_c^+) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst}) \\ R(\Lambda_c^+) = 0.242 \pm 0.026(\text{stat}) \pm 0.040(\text{syst}) \pm 0.059(\text{ext}) \end{cases}$$

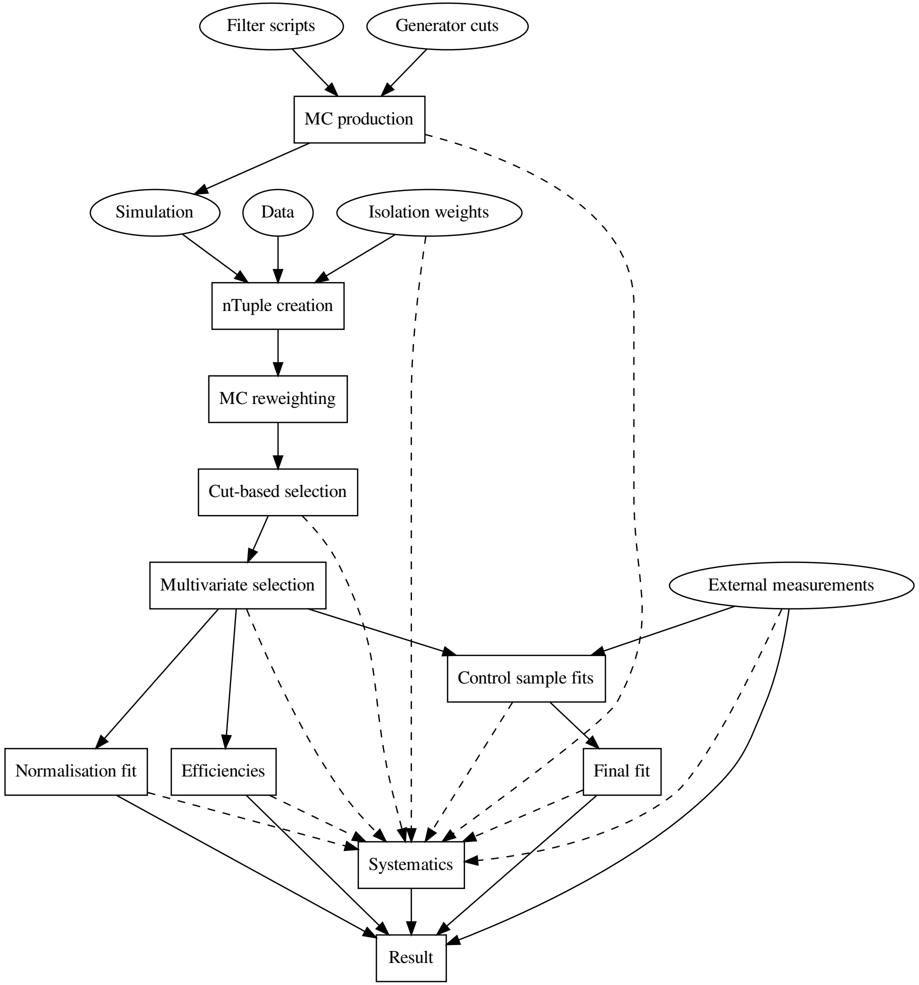
Agreement within 1.0σ to SM

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

Future of $R(X_c)$ at LHCb






Filter scripts
Generator cuts
MC production
Simulation
Data
Isolation weights
nTuple creation
MC reweighting
Cut-based selection
Multivariate selection
External measurements
Control sample fits
Normalisation fit
Efficiencies
Final fit
Systematics
Result