Lepton flavour universality measurements with flavour-changing charged currents at LHCb

LHCb Implications workshop 2023

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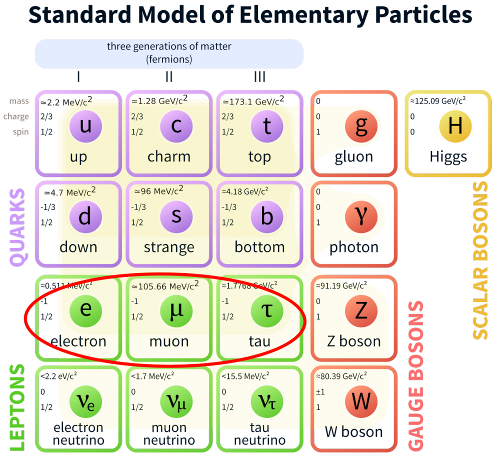
Tests of lepton flavour universality



[link]

In the Standard Model (SM)

- leptons almost the same
  - same electroweak couplings
  - but different masses

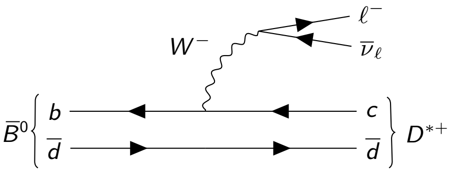
→ lepton flavour universality

- accidental symmetry

Violation of LFU would hint at presence of new physics

Tests of lepton flavour universality

LFU can be tested using tree-level semileptonic decays



- flavour-changing charged current
- large sample sizes
- theoretically clean

Semileptonic decays challenging at hadron colliders

- missing neutrino(s)
- many background sources
- signal yield needs to be extracted with template fits
- large and precisely calibrated simulated samples required

But profit from large sample sizes and production of various b-hadron species

Tests of LFU with complementary final states

Tests of lepton flavour universality

Test LFU at LHCb by measuring ratio of branching fractions

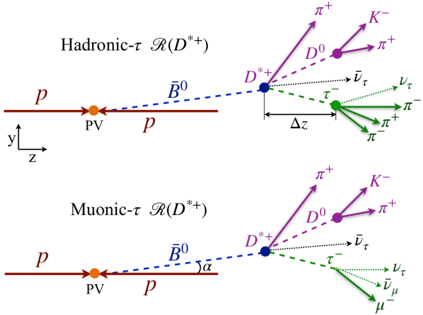
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \mu \overline{\nu}_\mu)}; \quad H_c = D^{*+}, D^0, D^+, D_s^+, \Lambda_c^+, J/\psi, \ldots$$

Powerful test of LFU

- theoretical uncertainties cancel to large extent
- reduced systematic uncertainty in efficiency ratio

Two ways of reconstructing τ at LHCb

- $\tau^+ \to \pi^+\pi^+\pi^-(\pi^0)\overline{\nu}_\tau$ (hadronic)
- $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$ (muonic)



Test of lepton flavor universality using $B^0 \to D^{*-}\tau^+\nu_\tau$ decays with hadronic τ channels [Phys. Rev. D 108 012018 (2023)]

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

Measure $B^0 \to D^{*-}\tau^+(\to \pi^+\pi^+\pi^-(\pi^0)\overline{\nu}_\tau)\nu_\tau$ w.r.t normalisation channel $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

$$\mathcal{R}(D^{*-}) = \underbrace{\left[\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}\right]}_{\mathcal{K}(D^{*-}),\textit{measured}} \times \underbrace{\left[\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right]}_{\textit{external}}$$

- requires external BF input to get $\mathcal{R}(D^{*-})$

Hadronic $\mathcal{R}(D^{*-})$ [PRD 108 012018 (2023)]

Use partial Run 2 dataset (2015, 2016: $2\,\mathrm{fb}^{-1}$) at $\sqrt{s} = 13\,\mathrm{TeV}$

- 40% more signal candidates than previous Run 1 measurement [PRD 97 072013 (2018)] [PRL 120 171802 (2018)]

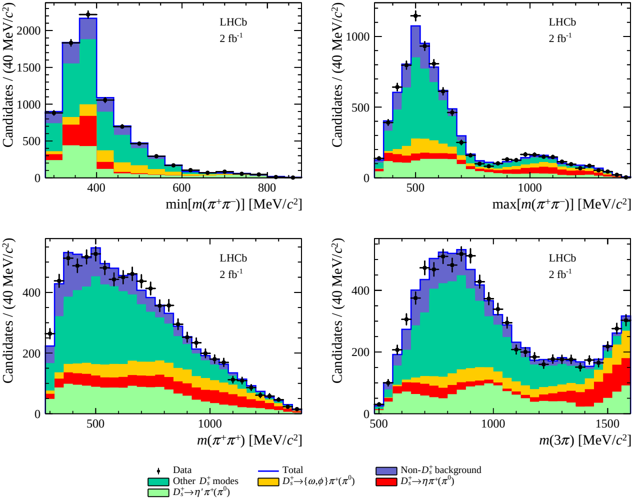
Main backgrounds

- 'prompt' $B \to D^* 3\pi$
  - suppressed by using displaced 3π vertex criterium
- double-charm $B \to D^{*-} D(X)$
  - $D = D_s^+, D^+, D^0$
  - suppressed by dedicated BDT (used as fit variable)

Extract signal using 3D template fit

- $q^2 = m^2(\tau^+ \nu_\tau)$
- τ^+ decay time t_{τ^+}
- output of BDT against $B^0 \to D^{*-} D_s^+(X)$

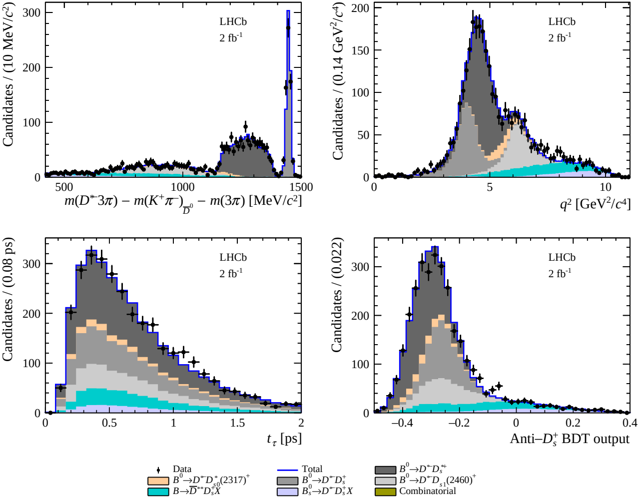
Control dynamics of $D_s^+ \to 3\pi^\pm X$ resonant structure using data



- fit 3π kinematic variables
- correct branching fractions used in simulation

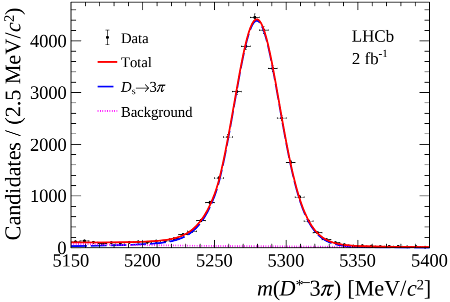
Hadronic $\mathcal{R}(D^{*-})$ [PRD 108 012018 (2023)]

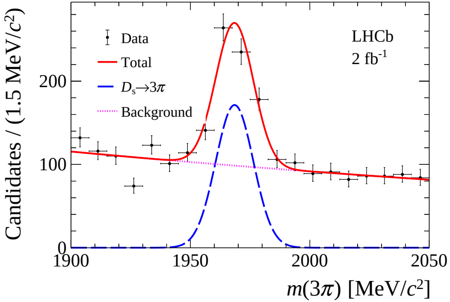
Control double-charm backgrounds $B \to D^{*-} D_s^+(X)$ using data



- fit $\Delta M_{D^* D_s^+} = m(D^{*-}3\pi) - m(\overline{D}^0) - m(3\pi)$
- provides constraints for signal fit

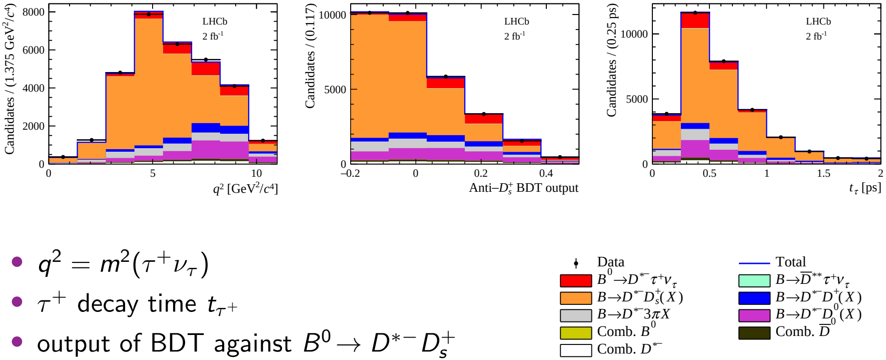
Extraction of normalisation mode $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ yield





- fit $m(D^{*-}\pi^+\pi^-\pi^+)$
- subtract contribution from $B^0 \to D^{*-}D_s^+(\to 3\pi)$

Extract signal using 3D template fit



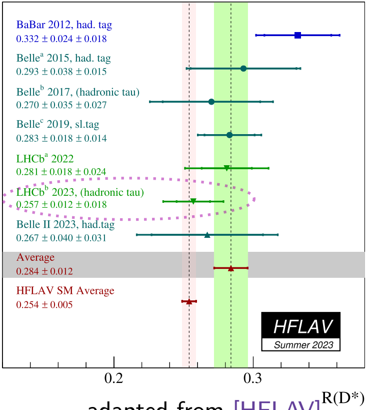
- $q^2 = m^2(\tau^+\nu_\tau)$
- τ^+ decay time t_{τ^+}
- output of BDT against $B^0 \to D^{*-}D_s^+$

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

- in agreement with Standard Model and world average

Hadronic $\mathcal{R}(D^{*-})$ [PRD 108 012018 (2023)]

Combined with LHCb Run 1 result [PRD 97 072013 (2018)] [PRL 120 171802 (2018)]



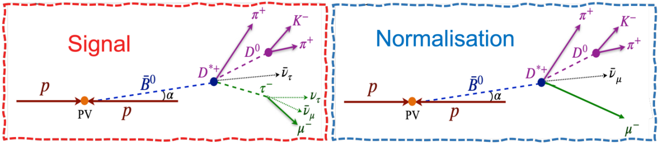
adapted from [HFLAV]

$$\mathcal{R}(D^{*-})_{comb} = 0.257 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.012\,(\text{ext})$$

Muonic $\mathcal{R}(D^0) - \mathcal{R}(D^*)$ [PRL 131 111802 (2023)]

Measurement of the Ratios of Branching Fractions $R(D^*)$ and $R(D^0)$ [Phys. Rev. Lett. 131 111802 (2023)]

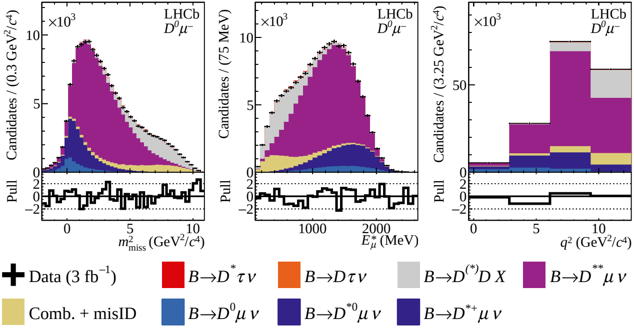
- measure $R(D^*)$ and $R(D^0)$ simultaneously with muonic τ decay
- uses Run 1 data ($3\,\text{fb}^{-1}$) at $\sqrt{s} = 7, 8\,\text{TeV}$
- supersedes [PRL 115 111803 (2015)]
- signal and normalisation sample same final state
  - no need for external BFs
- backgrounds from $B \to D^{**}\mu\nu_\mu$, $B \to DD(X)$



Two independent samples

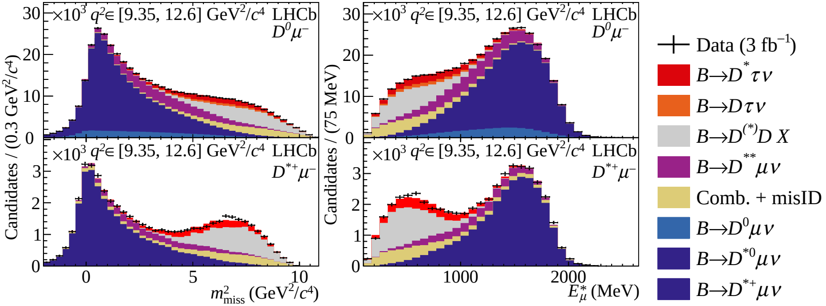
- $D^0\mu^-$
  - $B^- \to D^0(\to K^-\pi^+)\tau^-\overline{\nu}_\tau$
  - $B^- \to D^{*0}(\to D^0\not{\pi}^0/\not{\gamma})\tau^-\overline{\nu}_\tau$
  - $\overline{B}^0 \to D^{*+}(\to D^0\not{\pi}^+)\tau^-\overline{\nu}_\tau$
- $D^{*+}\mu^-$ (vetoed in $D^0\mu^-$ sample)
  - $\overline{B}^0 \to D^{*+}(\to D^0\pi^+)\tau^-\overline{\nu}_\tau$

Control backgrounds using samples with additional pions and kaons



- enriched in $B \to DDX$ and $B \to D^{**}\mu\nu$
- fit simultaneously with signal sample

Extract signal yield using 3D template fit

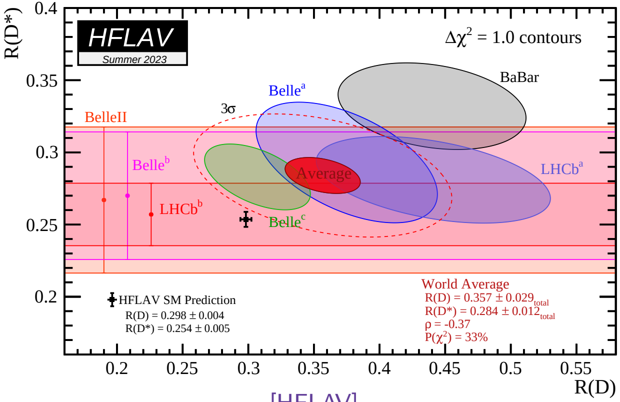


- fit variables $q^2 = m^2(\tau^+\nu_\tau)$, E^*_μ, m^2_{miss}

$$\mathcal{R}(D^*) = 0.281 \pm 0.018\,(\text{stat}) \pm 0.024\,(\text{syst})$$
$$\mathcal{R}(D^0) = 0.441 \pm 0.060\,(\text{stat}) \pm 0.066\,(\text{syst})$$
$$\text{correlation } \rho = -0.43$$

- in agreement with Standard Model at 1.9σ

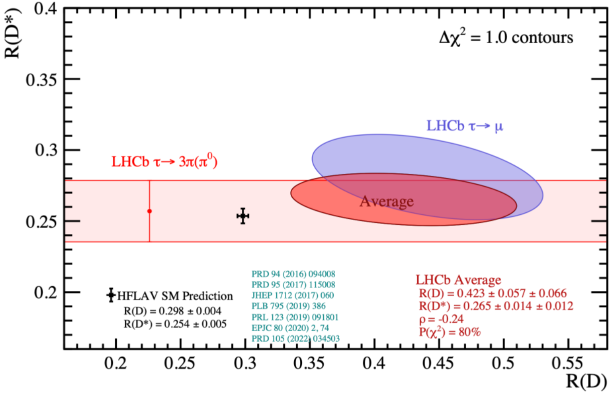
Global picture



[HFLAV]

Tension of about 3.3σ between average of measurements and SM predictions

Global picture



- precision on $R(D^*)$ reached by LHCb is similar to Belle
- main systematic uncertainties from simulated sample sizes and signal and background modelling

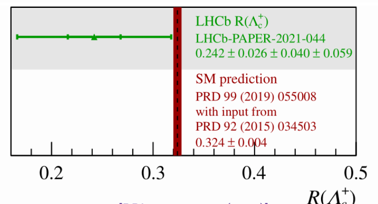
While semileptonic decays are very challenging at hadron colliders, LHCb is becoming major player

More ratios

Other b-hadrons used as well

- uniquely at LHC!
- probe different new physics scenarios with baryons

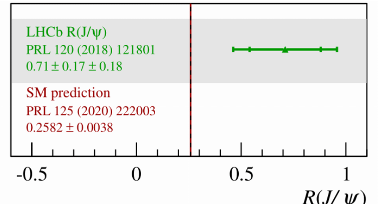
$\Lambda_b^0 \to \Lambda_c^+ \ell^- \overline{\nu}_\ell$ (Run 1, $3\,\text{fb}^{-1}$)



[PRL 128 191803 (2022)]

- using hadronic τ decay

$B_c^- \to J/\psi\, \ell^- \overline{\nu}_\ell$ (Run 1, $3\,\text{fb}^{-1}$)



[PRL 120 121801 (2018)]

- using muonic τ decay

Outlook

Much more data and final states to explore!

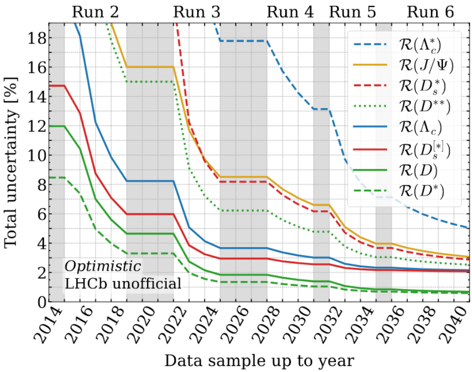
mode	Run 1 ($3\,\mathrm{fb}^{-1}$, 7/8 TeV) muonic	hadronic	Run 2 ($6\,\mathrm{fb}^{-1}$, 13 TeV) muonic	hadronic
$\mathcal{R}(D^+)$	✘	✘	✘	✘
$\mathcal{R}(D^0)$	✔	✘	✘	✘
$\mathcal{R}(D^*)$	✔	✔	✘	✔
$\mathcal{R}(\Lambda_c^+)$	✘	✔	✘	✘
$\mathcal{R}(\Lambda_c^{+*})$	✘	✘	✘	✘
$\mathcal{R}(J/\psi)$	✔	✘	✘	✘
$\mathcal{R}(D_s^+)$	✘	✘	✘	✘
$\mathcal{R}(D_s^{*+})$	✘	✘	✘	✘

In addition, work ongoing on

- $b \to u\ell\nu_\ell$ transitions
- excited states $\mathcal{R}(D^{**})$
- including more D decay modes

Outlook

Current Run 3 and beyond will further improve sensitivity



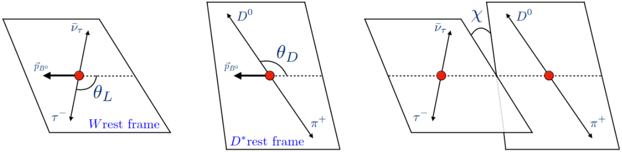
[Rev. Mod. Phys. 94, 015003 (2022)]

- many measurements statistically limited
- some systematic uncertainties can be reduced with more data
- large simulated samples required manageable with fast simulation techniques

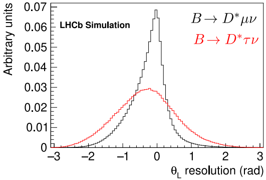
Outlook

Also performing angular analyses

- necessary to distinguish different NP models



- model-independent approach [JHEP11 133 (2019)]
- directly extract Wilson coefficients with HAMMER [EPJC 80, 883 (2020)]

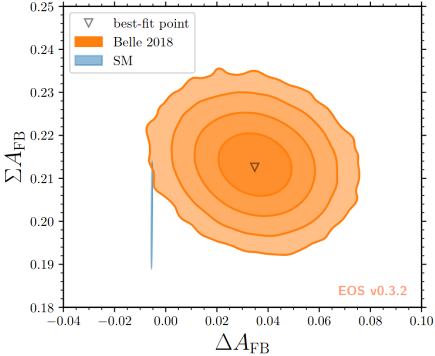


[CERN-LHCC-2018-027]

New measurement of D^* longitudinal polarisation fraction, see talk by Davide

Outlook

What about electrons? Is new physics hiding in angular observables?



[EPJC 8111, 984 (2021)]

Electrons more difficult to reconstruct due to Bremsstrahlung - ongoing analyses to establish feasibility

Summary

LHCb put two more points on the LFU table

- simultaneous measurement of $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$ - muonic
- $\mathcal{R}(D^{*-})$ - hadronic
- global average of $\mathcal{R}(D) - \mathcal{R}(D^*)$ measurements 3.3σ from SM prediction

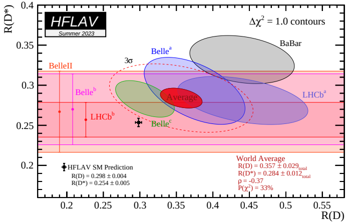
LHCb has unique samples to access various hadron species

- $\mathcal{R}(J/\psi)$, $\mathcal{R}(\Lambda_c^+)$

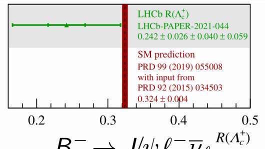
LHCb will further improve precision and add more final states and observables

- full Run 1+2, Upgrade I, Upgrade II
- angular analyses

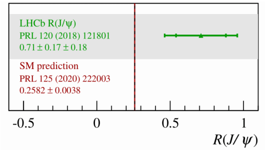
$B \to D^{(*)}\ell^-\overline{\nu}_\ell$



$\Lambda_b^0 \to \Lambda_c^+\ell^-\overline{\nu}_\ell$



$B_c^- \to J/\psi\,\ell^-\overline{\nu}_\ell$



Backup

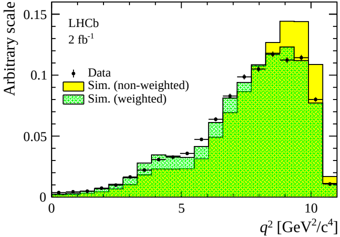
The different D_s^+ decay components are broadly divided into four categories:

- $D_s^+ \to \eta\pi^+(\pi^0)$ decays where charged pions from the η meson are selected;
- $D_s^+ \to \eta'\pi^+(\pi^0)$ decays where charged pions from the η' meson are selected;
- $D_s^+ \to \omega\pi^+(\pi^0)$ or $D_s^+ \to \phi\pi^+(\pi^0)$ decays where charged pions from the ω or ϕ meson are selected;
- D_s^+ decays where the pions originate either directly from the D_s^+ decay or from the a_1 resonance: $\eta 3\pi$, ηa_1, $\eta' 3\pi$, $\eta' a_1$, $\omega 3\pi$, ωa_1, $\phi 3\pi$, ϕa_1, $K^0 3\pi$, $K^0 a_1$, $\tau^+\nu_\tau$ and non-resonant 3π.

Hadronic $\mathcal{R}(D^{*-})$

[PRD 108 012018 (2023)]

Control double-charm backgrounds $B \to D^{*-} D^0(X)$, $B \to D^{*-} D^+(X)$ using data

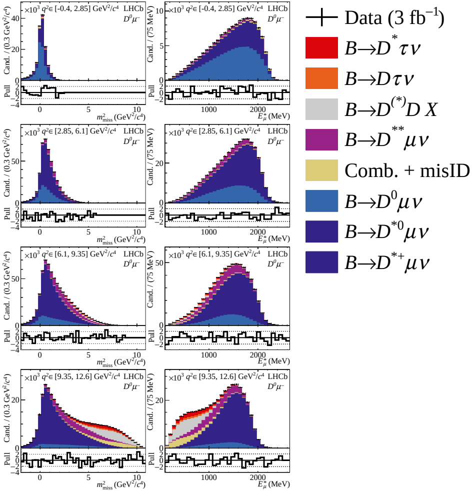


- correct simulated q^2 distribution

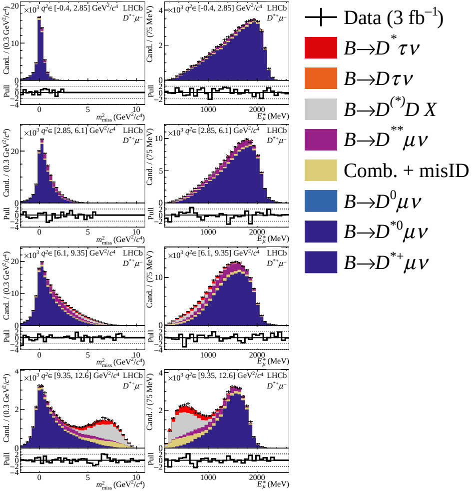
Systematic uncertainties

Source	systematic uncertainty (%)
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 $\overline{D}^{**}\tau^+\nu_\tau$ 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

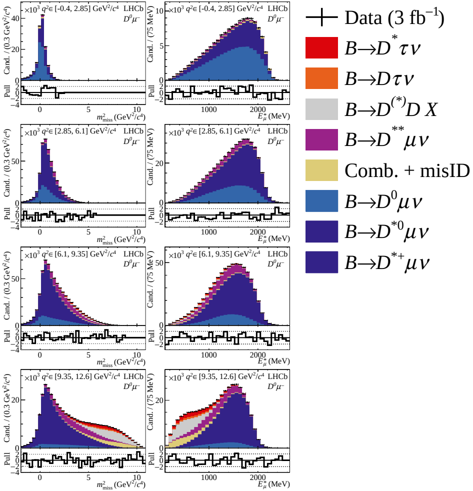
Extract signal yield using 3D template fit



Extract signal yield using 3D template fit



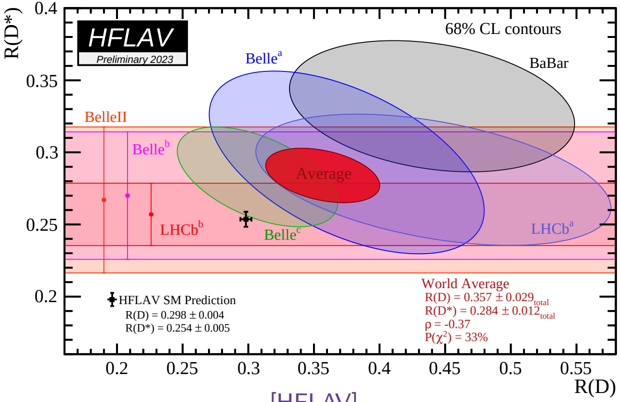
Extract signal yield using 3D template fit



Systematic uncertainties

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	-0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Baryonic backgrounds	0.7	1.2	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
Data/simulation corrections	0.4	0.8	
MisID template unfolding	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	-0.39
Total uncertainty	3.0	8.9	-0.43

Global picture



[HFLAV]