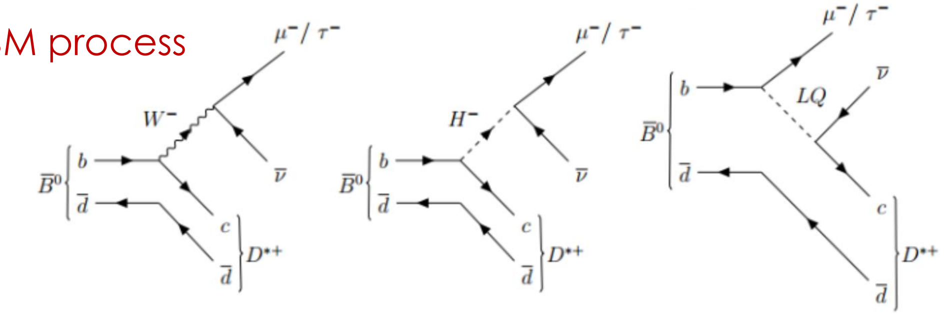
Flavour changing charged currents at LHCb

Lars Eklund, on behalf of the LHCb collaboration

Testing lepton flavour universality with semileptonic b-decays

SM process

BSM processes



Outline

- Lepton flavour universality in the SM
  - How to test this hypothesis with charged current decays
- Current theoretical and experimental status
- Recent results: measurements of $R(D^-)$ and $R(D^{*-})$
- New result: study of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays
- Conclusions

Lepton flavour universality (LFU)

- Lepton flavour universality: equal gauge boson coupling for all leptons
  - Phase space and hadronic effects influence the decay rates
- Tested in $W^{\pm}$ and Z decays

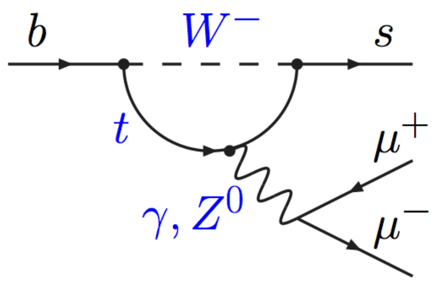
$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

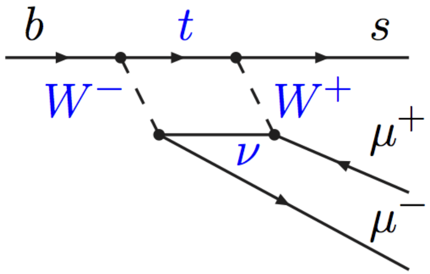
Phys. Rept. 427 (2006) 257

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

$$\frac{\Gamma_{\tau\nu}}{\Gamma_{\mu\nu}} = \frac{B(W^{\pm} \to \tau^{\pm}\nu_{\tau})}{B(W^{\pm} \to \mu^{\pm}\nu_{\mu})} = 0.992 \pm 0.013$$

Nature Physics 17, 813 (2021)



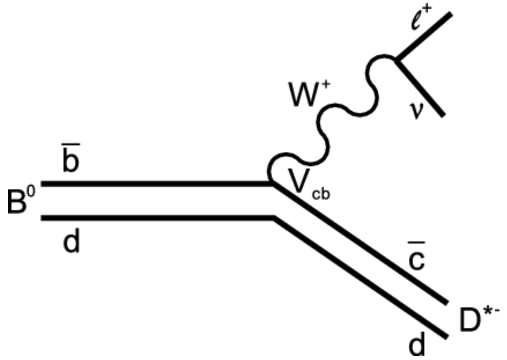


- Measure rates in heavy flavour decays
  - Flavour changing neutral currents Talk by C. Marin Benito

$$b \to s l^+ l^-$$

  - Flavour changing charged currents

$$b \to c l^- \bar{\nu}_l$$



LFU test with the $b \to c\tau^-\bar{\nu}_\tau$ / $b \to c\mu^-\bar{\nu}_\mu$ decay ratio

- Ratios of branching fractions
  - Cancellation of uncertainties
- Family of semileptonic decay ratios

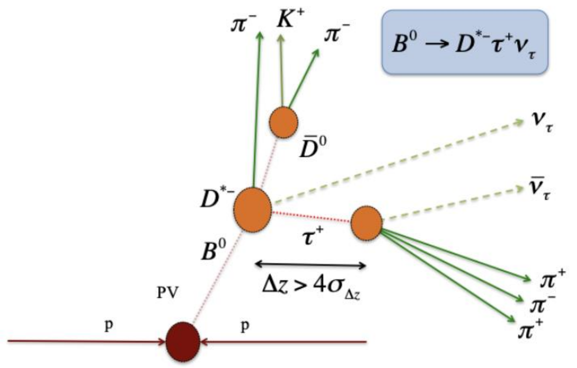
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\, \tau^-\, \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\, \mu^-\, \bar{\nu}_\mu)}$$

$$H_b = B^0, B^+, B_s^0, B_c^+, \Lambda_b^0$$

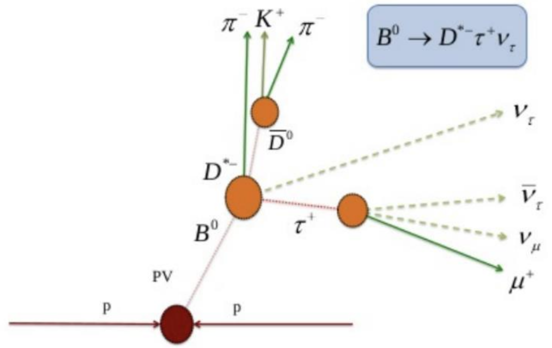
$$H_c = D^0, D^+, D_s^+, D^{*+/0}, D^{**+/0}, \Lambda_c^+, \Lambda_c^{*+}, J/\psi$$

- Neutrinos are not reconstructed in LHCb
  - Yields determined from fits with binned templates

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



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



*Charge conjugate modes are included

Semileptonic LFU measurements by LHCb

Muonic τ^- decays

Run 1 (2015) PRL 115 11803
$R(D^{*+}) = 0.336 \pm 0.027$ (stat) ± 0.030 (syst)

Run 1 (2023) PRL 131 11802
$R(D^{*}) = 0.281 \pm 0.018$ (stat) ± 0.024 (syst)
$R(D^{0}) = 0.441 \pm 0.060$ (stat) ± 0.066 (syst)

Run 2 (2024) PRL 134 061801
$R(D^{*+}) = 0.402 \pm 0.081$ (stat) ± 0.085 (syst)
$R(D^{+}) = 0.249 \pm 0.043$ (stat) ± 0.047 (syst)

Run 1 (2018) PRL 120 121801
$R(J/\psi) = 0.71 \pm 0.17$ (stat) ± 0.18 (syst)

Hadronic τ^- decays

Run 1 (2018) PRL 120 171802
$R(D^{*+}) = 0.291 \pm 0.019$ (stat) ± 0.026 (syst) ± 0.013 (ext)

Part of run 2 (2023) PRD 108 (2023) 012018 Erratum
$R(D^{*+}) = 0.260 \pm 0.015$ (stat) ± 0.016 (syst) ± 0.012 (ext)

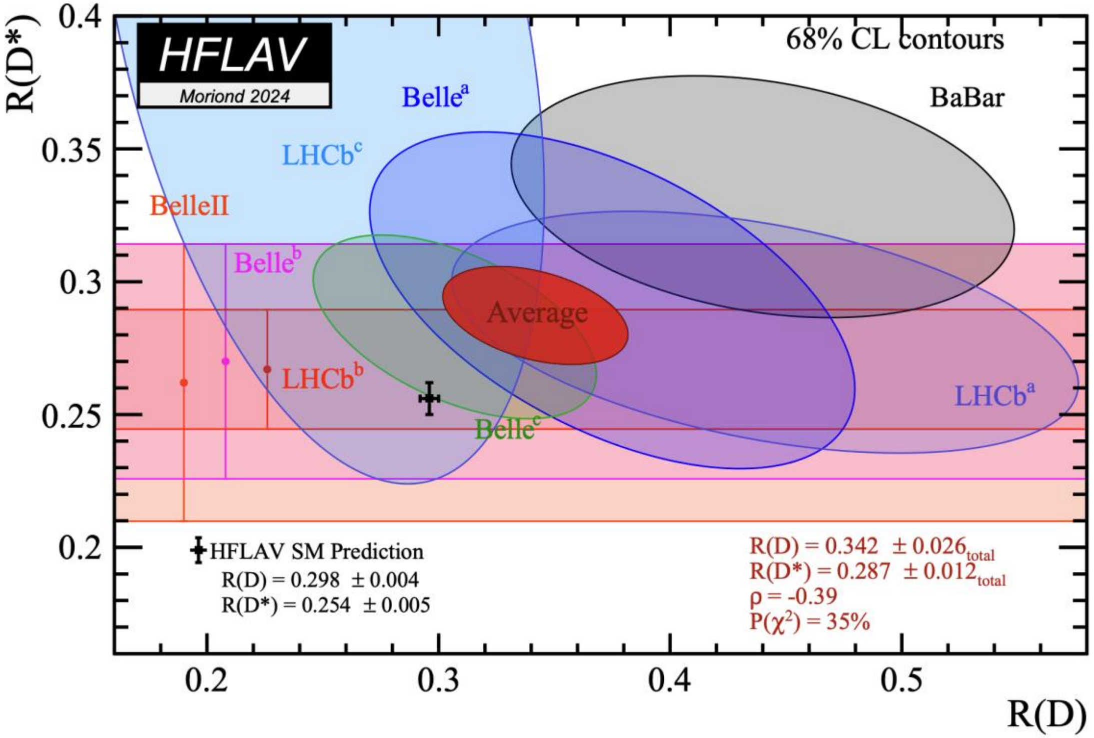
Run 1 (2022) PRL 128 191803
$R(\Lambda_c^+) = 0.242 \pm 0.026$ (stat) ± 0.040 (syst) ± 0.059 (ext)

Run 1 & part of run 2 (2023), longitudinal polarisation
$F_L^{D^*} = 0.41 \pm 0.06$ (stat) ± 0.03 (syst) PRD 110 092007

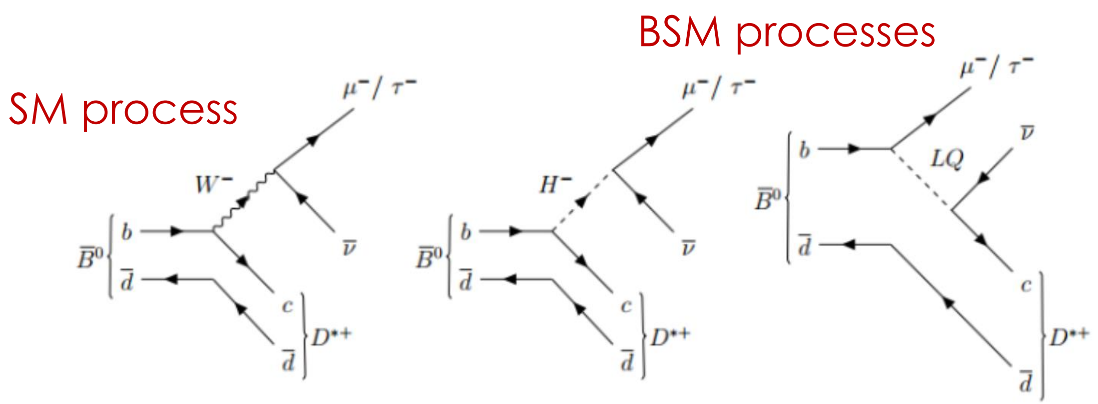
Run 1 & 2 (2025) LHCb-PAPER-2024-037: presented today
$R\left(D_{1,2}^{**0}\right) = 0.13 \pm 0.03$ (stat) ± 0.01 (syst) ± 0.02 (ext)

Experimental and theoretical status for $R(D^{(*)})$

- HFLAV average of $R(D^{(*)})$
  - 3.3σ deviation from the SM prediction



- BSM processes may affect these ratios
  - Leptoquarks, two Higgs doublet, non-universal left-right models, …



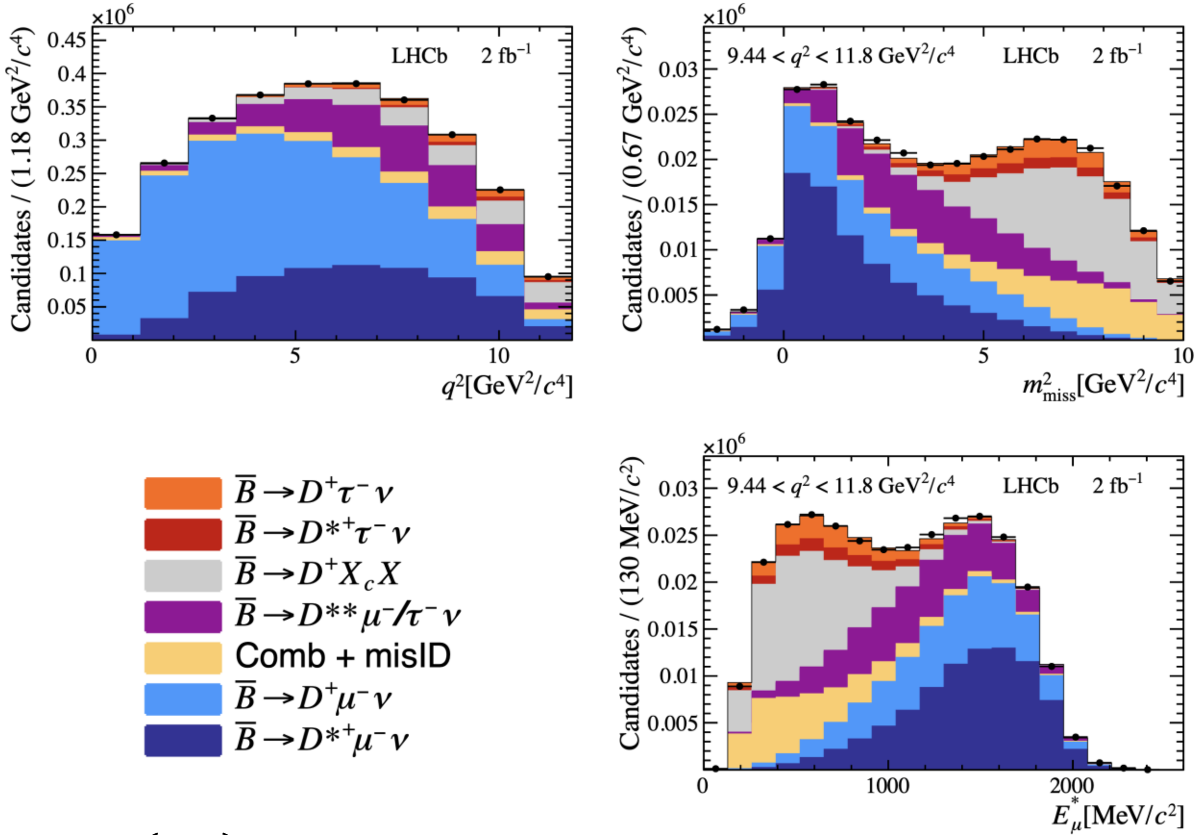
PRD 94 (2016) 034001 PRD 87 (2013) 014014

- Angular analysis gives additional sensitivity
  - E.g. triple product asymmetries PRD 90 (2014) 074013

$R(D^+)$ and $R(D^{*+})$ with muonic τ^- decays

PRL 134 061801

- Data collected in 2015 – 2016 with $\int \mathcal{L} = 2$ fb^{-1}
- Measure $\mathcal{B}(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu)$
  - $D^{*+} \to D^+\pi^0$, (π^0 not reconstructed)
  - $D^+ \to K^-\pi^+\pi^+$
- Yields determined from a 3D fit
  - $q^2 = (p_{B^0} - p_{D^{(*)-}})^2$
  - E_μ^*: muon energy in B^0 rest frame
  - $m^2_{miss} = (p_{B^0} - p_{D^{(*)-}} - p_{\mu^+})^2$
  - Templates determined from simulation and control samples



$R(D^-) = 0.249 \pm 0.043 \pm 0.047$

$R(D^{*-}) = 0.402 \pm 0.081 \pm 0.085$

Correlation: $\rho = -0.39$

Measurement of $R(D^{*+})$ with hadronic τ^- decays

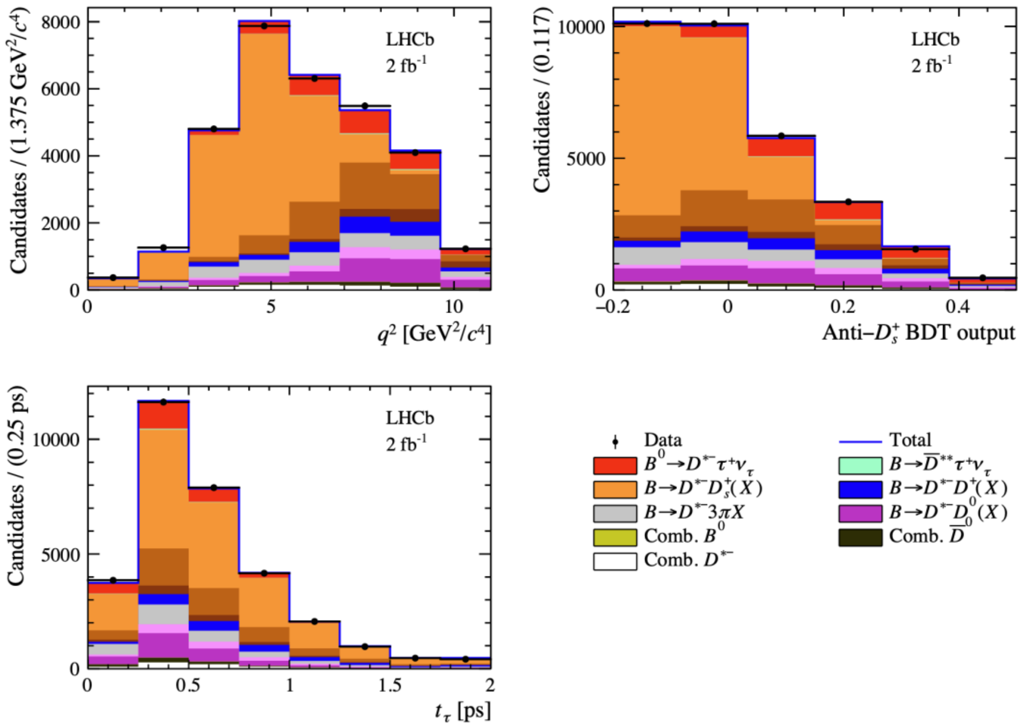
PRD 108 (2023) 012018 Erratum

- Data collected in 2015 – 2016 with $\int \mathcal{L} = 2$ fb^{-1}

- Measure $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)$, with $D^{*+} \to D^0\pi^-$
  - Normalised to $\bar{B}^0 \to D^{*+}\pi^-\pi^-\pi^+$
  - Using known $\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ gives

$$R(D^{*+}) = 0.260 \pm 0.015 \pm 0.016 \pm 0.012$$
$$R_{comb}(D^{*+}) = 0.267 \pm 0.012 \pm 0.015 \pm 0.013$$

- The yield determined from a 3D fit
  - $q^2 = (p_{\bar{B}^0} - p_{D^{*+}})^2$
  - Anti-D_s^+ BDT output
  - t_τ: tau decay time
  - Templates determined from simulation and control samples



- Background $B^0 \to D^{**}\tau^-\nu_\tau$ with $D^{**} \to D^{*+}\pi$
  - Set to 3.5% from predictions and known $\mathcal{B}$
  - These assumptions require verification

Study of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays by LHCb

Submitted to PRL
arXiv:2501.14943

- D^{**} states that could enter $R(D^*)$
  - Decay to $D^{*-}\pi^+$

$D_1'(2400)^0$, $m = 2412 \pm 9$ MeV/c², $\Gamma = 314 \pm 29$ MeV/c²

$D_1(2420)^0$, $m = 2422.1 \pm 0.6$ MeV/c², $\Gamma = 31.3 \pm 1.9$ MeV/c²

$D_2(2460)^0$, $m = 2461.1 \pm 0.8$ MeV/c², $\Gamma = 47.3 \pm 0.8$ MeV/c²

  - D^{**0}: sum of all three in this analysis
  - $D^{**0}_{1,2}$: sum of $D_1(2420)^0$ and $D_2(2460)^0$

- Goals of the analysis
  - Search for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays
  - Measure $\mathcal{B}\left(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau\right) \times \mathcal{B}(D^{**0}_{1,2} \to D^{*+}\pi^-)$
  - Measure $R\left(D^{**0}_{1,2}\right) = \frac{\mathcal{B}(B^0\to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^0\to D^{**0}_{1,2}\mu^-\bar{\nu}_\mu)}$
    - SM prediction 0.09 ± 0.02

PRD 97 (2018) 075011 | JHEP 05 (2022) 29 | arXiv:2102.11608

- Measured normalised to $\mathcal{B}\left(B^- \to D^{**0}_{1,2}D_s^{(*)-}\right)$
  - Its $\mathcal{B}$ is determined from $\mathcal{B}$ measurement and amplitude analysis of $B^+ \to D^{*-}D_s^+\pi^+$ JHEP 08 (2024) 165
  - Increased statistics by combining D_s^- and D_s^{*-}

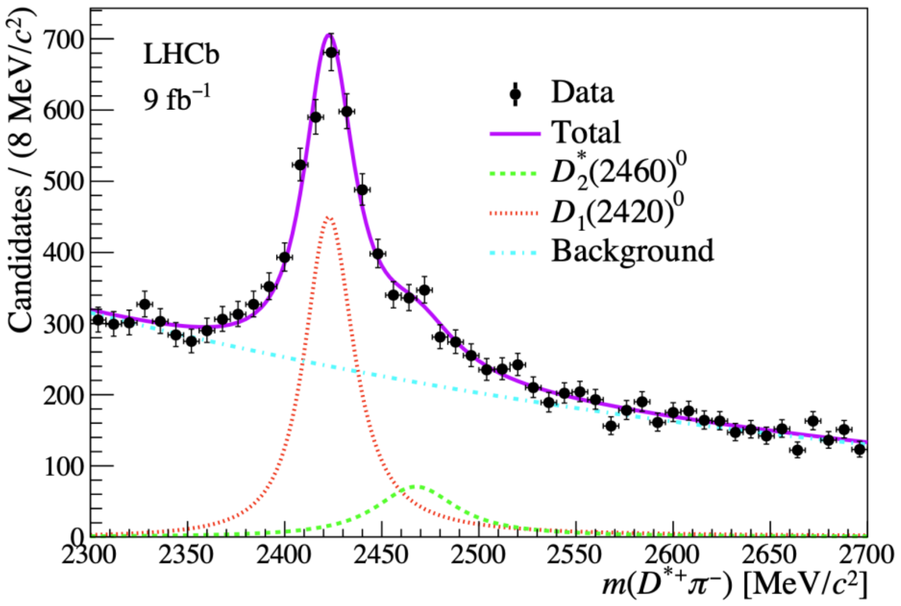
*The $D_1'(2400)^0$ is called $D_1(2430)^0$ in the PDG

Selection of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$

Submitted to PRL
arXiv:2501.14943

- Run 1 & 2 dataset: $\int\mathcal{L} = 9$ fb^{-1}
  - Hadronic τ^- decays
- Trigger and pre-selection requirement
- Flight distance requirement on the τ^-
  - Suppresses prompt $B \to D^{**0}\pi^-\pi^-\pi^+(X)$
- Three multivariate BDTs to reject:
  - Fake D^{**0} candidates
  - Multibody D_s^+ with track swap
  - $D_s^+ \to \pi^+\pi^-\pi^+(X)$ mimicking τ^+ (anti-D_s^+)
- Fit to $D^{*+}\pi^-$ to spectrum without anti-D_s^+ BDT
  - Investigate components of the decay
  - Not possible to distinguish the broad $D_1'(2400)^0$ from combinatorial background

Selected mass spectrum, w/o the anti-D_s^+ BDT

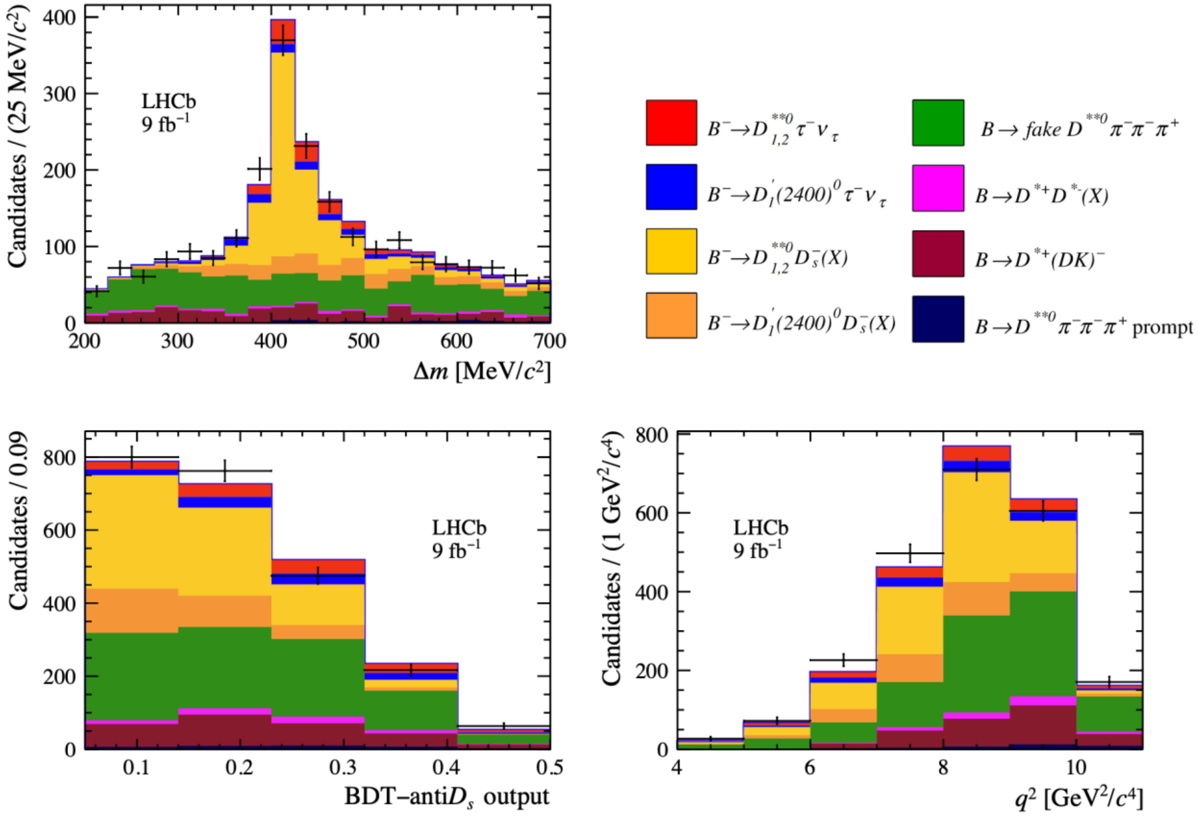


2456 ± 75 $D_1(2420)^0$ candidates
633 ± 69 $D_2^*(2460)^0$ candidates

Fit to determine the $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ yields

Submitted to PRL
arXiv:2501.14943

- 3D binned fit to extract the yields
  - $\Delta m = m_{D^{**0}} - m_{D^{*+}}$
  - Anti-D_s^+ BDT output
  - $q^2 = (p_{B^0} - p_{D^{*-}})^2$= m² of the $\tau^-\bar{\nu}_\tau$ system
- Signal templates determined from simulation
  - Combined $D_1(2420)^0$ and $D_2^*(2460)^0$ template
  - Relative size of $D_1(2420)^0$, $D_2^*(2460)^0$ and $D_1'(2400)^0$ fixed from predictions
- Backgrounds from simulation and control samples
- Control samples from data
  - D^0 and D^{*+} sidebands
  - Wrong-sign $D^{*\pm}\pi^\pm$ combinations (WS)
  - Removing the τ^- flight distance requirement
  - Selecting $m(\pi^+\pi^-\pi^+)$ close to D_s^+ mass
  - Removing anti-D_s^+ BDT requirement
  - …



123 ± 23 $B^- \to D_{1,2}^{**}\tau^-\bar{\nu}_\tau$ candidates

220 ± 34 $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ candidates

$B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ results

Submitted to PRL
arXiv:2501.14943

- 3.5σ significance for for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$
  - Pure $D_2(2460)^0$ contribution excluded at 2.7σ

- Branching ratio measurement
  - Primary quantity: $\kappa = \frac{\mathcal{B}(B^0 \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D_{1,2}^{**0}D_s^{(*)})} = 0.19 \pm 0.04$

$$\mathcal{B}\left(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau\right) \times \mathcal{B}\left(D_{1,2}^{**0} \to D^{*+}\pi^-\right) = (0.051 \pm 0.017)\%$$

- LFU ratio measurement
  - Uses known $\mathcal{B}(B^0 \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)$

PRD 107 (2023) 092003 | PRL 103 (2009) 051803 | PRD 77 (2008) 091503 | PRL 101 (2008) 261802

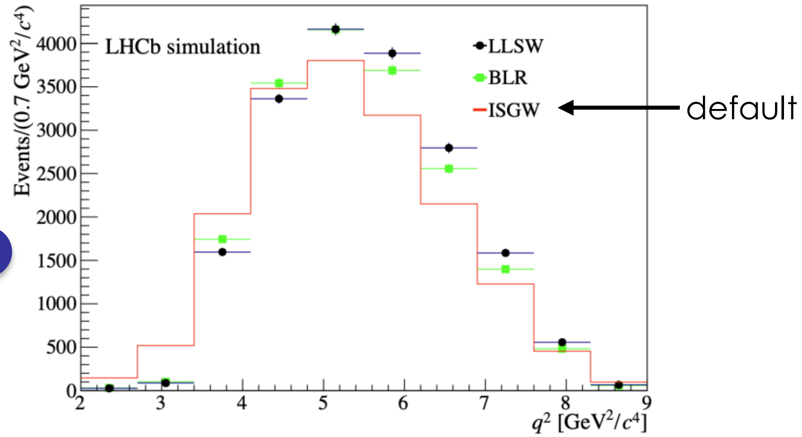
$$R\left(D_{1,2}^{**0}\right) = \frac{\mathcal{B}(B^0 \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)} = 0.13 \pm 0.04$$

  - Agrees with SM prediction 0.09 ± 0.03

PRD 97 (2018) 075011
PRD 38 (1989) 799
PRD 57 (1998) 308

Systematic uncertainty on κ	
Decay model	3.7%
$D_1(2420)^0/D_1(2420)^0$ ratio	4.4%
Simulation sample size	5.9%
Binning scheme	5.0%
$B^- \to D^{**0}(DK)^-$ contamination	3.6%
Selection efficiency	2.0%
τ^- flight distance requirement	4.0%
WS background description	2.0%
Total	11.4%

$D_2^*(2460)^0$ q^2 distribution for three decay models



Conclusions and comparison with $R(D^{*-})$ analysis

- SM has the same gauge boson coupling for all leptons

- Semileptonic decay ratios test this assumption

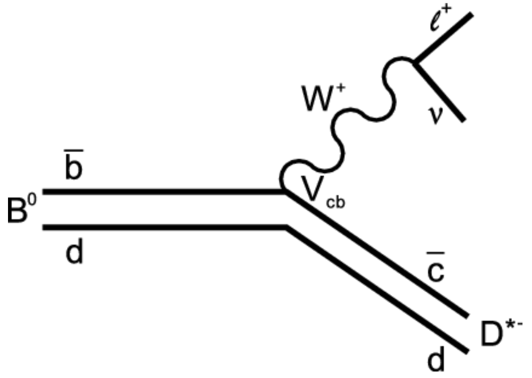
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu)}{\mathcal{B}(H_b \to H_c \mu \nu)}$$

- Study of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays
  - Evidence for this family of decays
  - Branching ratio measurement

$$\mathcal{B}\left(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau\right) \times \mathcal{B}\left(D_{1,2}^{**0} \to D^{*+}\pi^-\right) = (0.051 \pm 0.017)\%$$

  - Lepton flavour universality ratio

$$R\left(D_{1,2}^{**0}\right) = \frac{\mathcal{B}(B^0 \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^0 \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)} = 0.13 \pm 0.04$$



PRD 108 (2023) 012018

- Estimate D^{**0} yield in $R(D^{*-})$ hadronic
  - $(8.9 \pm 2.1)\%$ and $< 13.1\%$ at 95% C.L.
    - Assumed 3.5% – compatible 2.6σ
  - Corresponds to a shift in $R(D^{*-})$ of 0.013
    - Covered by the assigned uncertainty

- Important input for future measurements

Several semileptonic LFU measurements are in the pipeline

Analyses with run 3 data are in progress

THANK YOU FOR YOUR ATTENTION