Anatomy of $B \to D^{*(*)}\tau\nu_\tau$ at LHCb: rates, polarization and form factors

MITP - Flavourful Opportunities in Semileptonic B Decays: Connecting Theory and Experiment

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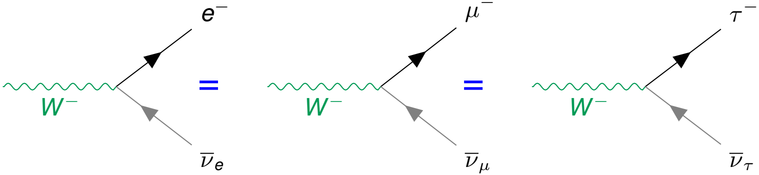
Introduction

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



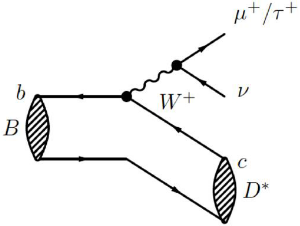
- Semileptonic b-hadron decays provide a powerful probe for testing the SM and search for New Physics (NP) effect:
  - **leptoquarks** PRD 94, 115021, ...
  - **two Higgs doublet models** PRL 116, 081801, ...
  - **Heavy vector bosons**, e.g. W' JHEP 07 (2015) 142 1506.01705, ...

Interesting measurements:

- Lepton flavour universality (LFU): $\mathcal{R}(H_c) \equiv \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell^+ \nu_\ell)}$
- CKM parameters: $|V_{cb}|$, $|V_{ub}|$
- Form factors and angular observables

Semileptonic decays at LHCb

- Tree level $\Longrightarrow$ abundant
- Theoretically clean
  - factorize hadron and lepton current
  - hadron current described by form-factors
- Experimentally tricky due to ≥ 1 missing ν_ℓ



Advantages

- Large H_b production
- Produce B^+, B^0, B_s^0, B_c^+, Λ_b^0, etc.
- Boosted H_b
- Efficient tracking $\Longrightarrow$ isolation

Challenges

- No beam-energy constraint
- Significant backgrounds (combinatorial + partially reco)
- Reliance on simulation
  - large samples are required

$R(H_c)$ status

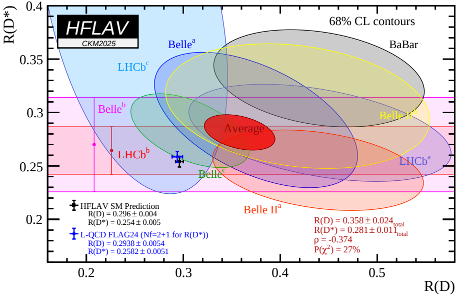
- Powerful tests of LFU from ratios of branching fractions of B decays to different leptons
  - hadronic uncertainties mostly cancel in the ratio $\rightarrow$ precise theory predictions
  - Reduced experimental systematic uncertainties in ratios of efficiencies

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

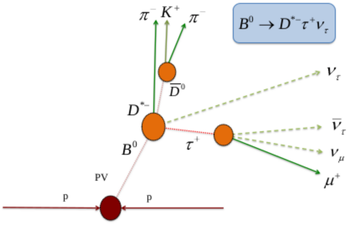
- Measurements done for several b and c hadrons
  - Most precise for $B \to D^{(*)}\ell\nu$
- SM predictions very precise:

$$R(D^+) = 0.298 \pm 0.004$$
$$R(D^{*+}) = 0.254 \pm 0.005$$

- LHCb measurements done with muonic PRL 131, 111802, PRL 134, 061801 and hadronic tau decays PRD 108, 012018
- World average in 3.8σ tension from SM in 2025.

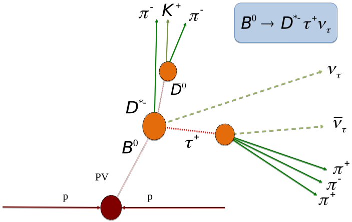


Muonic τ decay



- Direct measurement of $R(X_c)$
- High statistics
- Good control of systematics
- Sensitive to $D^{**}\mu^-\nu_\mu$
- Main backgrounds:
  - mis-identified μ
  - $H_b \to H_c D_(s)^{(*)}$

Hadronic τ decay



- High purity sample
- τ vertex reconstruction and specific dynamics of $\tau^+ \to 3\pi^\pm\bar{\nu}_\tau$
- $R(X_c)$ requires external inputs
- Low statistics
- Main backgrounds:
  - prompt Hb→Hc3p(X)
  - double charmed decays with $D_s^{(*)} \to 3\pi(X)$

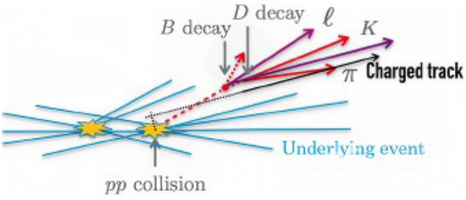
B semileptonic decays: common methods and tools

- Signal: $B \to D^{(*)}\tau^-(\to \mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau$ or $\tau^- \to \pi^-\pi^-\pi^+(\pi^0)\nu_\tau$.
- **At least two neutrinos** in the final state $\Rightarrow$ no B invariant mass peak,

  $\Longrightarrow$ use B flight direction to measure transverse component of missing momentum

  longitudinal component approximated with boost of the visible final state
  $\gamma\beta^B_{z,total} = \gamma\beta^B_{z,visible}$
  to access rest frame kinematics $\to \sim$ 20% resolution on B momentum

- Large backgrounds from partially reconstructed B decays $B \to D^{**}\mu\nu$, $B \to (D \to X\mu)D^*X$ with many unknowns (form factors, decay rate, etc.)
- require isolated D vertex è multivariate classifiers MVA



Data

- Data-derived templates for misID and combinatorial backgrounds
- PID and tracking efficiencies from data control samples

Simulation

- MC templates for signal, normalization and physics background
  - detailed tuning of MC templates with data/simulation corrections
  - size of simulated sample is a limit for final precision
- Fast simulation techniques:
  - ReDecay MC: underlying event fixed while generating signal candidates
  - tracker-only MC: RICH photon propagation and Calo showers are turned off

$\Longrightarrow$ up to $\times 8$ faster and 40% less disk space

$\Longrightarrow$enable to produce large amount of MC samples

Hammer tool [Eur. Phys. J. C. 80 (2020) 883]

- HAMMER is a tool for efficient reweighing of MC events of semileptonic b decays to any BSM theory and/or Form Factor (FF) description of hadronic matrix elements

Helicity Amplitude Module for Matrix Element Reweighting

- Two tools developed by LHCb interface HAMMER and fitting frameworks directly
  - form factor parameters can be directly varied in fits to data
  - incorporate speedups of HAMMER

RooHammerModel
arXiv:2007.12605

- C++ based interface to RooFit / HistFactory
- Behaves as a standard pdf, but checking if any FF parameter or WC has changed since the last evaluation step

$\Longrightarrow$ if so, it calls HAMMER to reweight the histogram.

Redist-HAMMER
Colonna et al., Python in Science (2025)

- Python based interface to Pyhf (Heinrich et al., Journal of Open Source Software (2021)), using redist (arXiv:2402.08417)
- Introduces custom modifies of the likelihood varying shapes:

$$pdf(C_i, FFs, ...) = pdf_{null} \times \frac{pdf_{alt}(C_i, FFs, \ldots)}{pdf_{null}}$$

$B^0 \to D^{*-}\ell^+\nu_\ell$ form factors

- $B \to D^{(*)}$ transitions described by hadronic form factors, functions of q^2 (or recoil variable w).

$$\frac{d\Gamma(B^0 \to D^* \ell\nu_\ell)}{dq^2} = \frac{G_F^2|V_{cb}|^2|\eta_{EW}|^2|\vec{p}|^2 q^2}{96\pi^3 m_{B^0}^2}\left(1-\frac{m_\ell^2}{q^2}\right) \times \left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1-\frac{m_\ell}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2\right]$$

BGL PRL 74 (1995) 4603

- Bayesian Information Criterion used to optimized the order of fitting parameters:

  $$BIC = \chi^2 + k\ln(n)$$

  - k = number of parameters
  - n = sample size

CLN Nucl. Phys. B 530 (1998) 1

- Uses dispersion relations and reinforced unitarity bounds based on HQET to reduce the number of free parameters

BLPR PRD 95 (2018) 115008

- HQET parametrization for hadronic matrix elements
- Improved calculations using leading and $O(\Lambda_{QCD}/m_b)$ Isgur-Wise function

- Systematic uncertainties on the form factors are estimated:
  - **varying the parameters of the chosen model** according to their uncertaities and correlations (neglected if the templates are free to float in the fit)
  - repeating the fit with **alternative parametrizations**

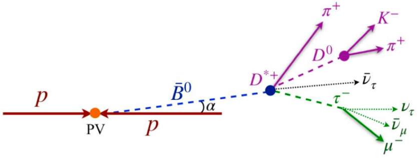
$R(D^{(*)})$ measurements

Combined $R(D)$ and $R(D^*)$ muonic at LHCb [Phys. Rev. Lett. 134 (2025) 061801]

- Simultaneous measurement of $R(D)$ and $R(D^*)$ using muonic τ decays

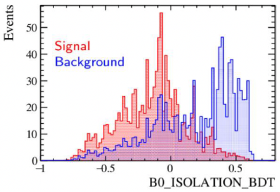
$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)}, \qquad \tau^- \to \mu^-\nu_\mu\nu_\tau, \qquad D^{*-} \to D^0(\to \pi^+K^-)\pi^-$$

- Using Run1 and a part of Run2 data (2015-2016)
- $B^0 \to D^{*,+}\tau^-\nu_\tau$ with $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ $\mathcal{B} \sim 17.4\%$, with $D^{*+} \to (D^+ \to K^+\pi^-\pi^+)\pi^0$
- 3 neutrinos in the final state complicate the kinematics. (poorer resolution than hadronic mode).



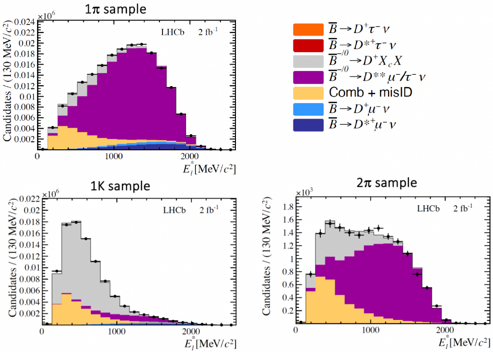
Analysis strategy:

- 3D simultaneous fit to signal and control channels: m^2_{miss}, E^*_ℓ, $q^2 = (P_B - P_{D^*})^2$
- Background from excited D** states studied in control regions
- Signal efficiency from corrected simulated samples.



Combined $R(D)$ and $R(D^*)$ muonic at LHCb [Phys. Rev. Lett. 134 (2025) 061801]

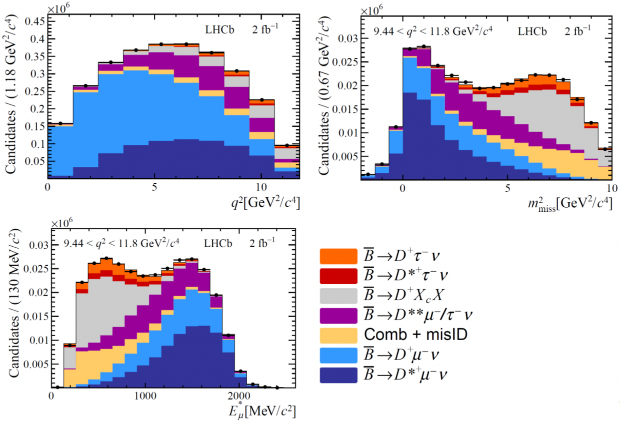
- Physics backgrounds with additional charged tracks rejected with isolation discriminant
- Inverting the cut provides control samples enriched in background ($D^{(*)}\mu + 1\pi, 2\pi, 1K$)
- Used to constrain background modelling.
- Background from misidentified muons and combinatorial also from data samples.
- Maximum likelihood fit to isolated signal regions and anti-isolated control regions



Combined $R(D)$ and $R(D^*)$ muonic at LHCb [Phys. Rev. Lett. 134 (2025) 061801]

- Fit projection in the isolated signal region:

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$
$$\rho = -0.39$$



- In agreement with R(D*)-R(D) world-average, 1.9σ above the SM prediction.
- Main systematic uncertainties: limited size of simulated sample and effect of shape parameters derived from control regions.

Combined $R(D)$ and $R(D^*)$ muonic at LHCb [Phys. Rev. Lett. 134 (2025) 061801]

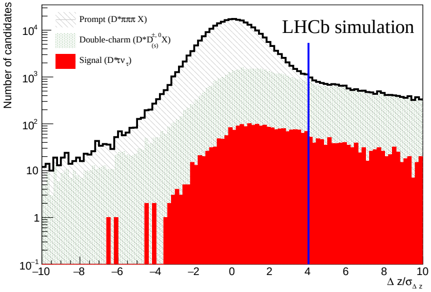
Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\bar{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\bar{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

Dominant source of systematic are:

- Limited size of the simulation samples
- Form factor parameterization
- Modelling of the backgrounds
- D^{**} feed-down contribution
- Form factor model

$R(D^*)$ hadronic measurement [Phys. Rev. D 108, 012018]

- Using 2015-16 (Run 2) data considering hadronic τ decays
- Advantages of hadronic the decay mode:
  - only 1 neutrino in the τ decay: $\Longrightarrow$ event kinematic is properly reconstructed
  - good purity $\Longrightarrow$ strong background rejection



[Phys. Rev. D 97, 072013]

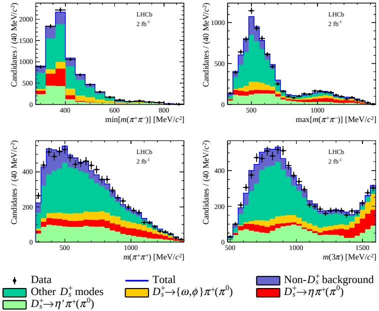
Dominant backgrounds

- Prompt decay $B \to D^{*-} 3\pi^{\pm} X$
  - 3π system from the B meson
  - $\sim 100\times$ signal decays
  - requiring a 3π vertex detached by the B vertex along the beam axis
  - additional BDT in Run 2 to reach Run 1 rejection level: > 99.9%
- Double charm $B \to D^{*-} D^{+,0}_{(s)} X$ decays
  - signal like topology
  - detached vertex due to non-negligible lifetime
  - rejected through isolation algorithm and dedicated MVA classifiers in the D mass region reconstructed in exclusive decay modes

Modelling of D_s in $B \to D^{*-} D_s(X)$ decays[Phys. Rev. D 108, 012018]

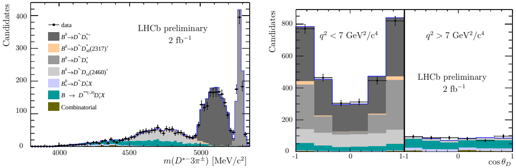
Decays of D_s [arXiv:2305.01463]

- $D_s \to 3\pi^{\pm} X$ branching fractions are not well known or correctly simulated
- Data sample selected using D_s BDT output
- Simultaneous fit to: min$[m(\pi^+\pi^-)]$, max$[m(\pi^+\pi^-)]$, $m(\pi^+\pi^+)$, $m(3\pi)$
- D_s fractions used to correct simulation



Production of D_s [LHCb-PAPER-2023-020]

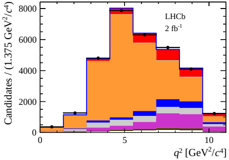
- D_s meson arises from $B \to D^{*-} D_s^{+(*,**)} X$
- Poor knowledge on their relative fractions
- Enriched data sample of $D^{*-} D_s X$ decays reconstructed from $D_s \to 3\pi^{\pm}$ mode
- Fraction with respect the $D^* D_s^{*+}$ channel determined through a fit to the $m(D^{*-}3\pi)$
- Values are used to constrain the various component in the final fit

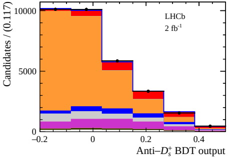


- Measurement of $R(D^*)$ with partial Run 2 data using hadronic τ decays

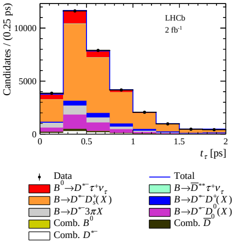
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}, \qquad R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \right\}_{external}$$

- Fit performed using 3D binned template
  - $q^2 \equiv (p_{B^0} - p_{D^*})^2$
  - τ decay-time
  - anti-D_s BDT output
- Main background:
  - prompt $B \to D^* 3\pi^\pm X$ (strongly suppressed)
  - double charm $B \to D^* D_{(s)}(\to 3\pi^\pm X)X'$





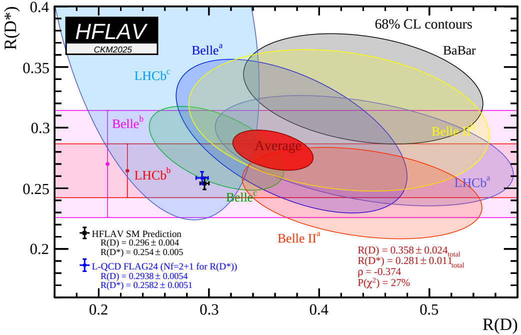
$$R(D^*)_{Run\ 2} = 0.247 \pm 0.015(stat) \pm 0.015(syst) \pm 0.012(ext)$$
$$R(D^*)_{Run\ 1-2} = 0.257 \pm 0.012(stat) \pm 0.014(syst) \pm 0.012(ext)$$

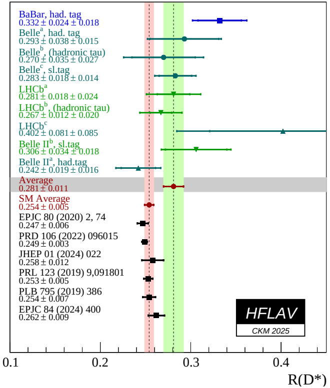


Agreement to SM within 1σ

- Main systematic uncertainties:
  - limited size of simulated samples
  - signal/background modelling

Current $R(D) - R(D^*)$ scenario [HFLAV]





- Deviation of the $R(D) - R(D^*)$ combination: 3.2σ

$F_L^{D^*}$ measurement in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

Longitudinal D^* polarization fraction

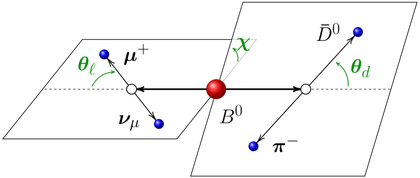
- Angular analyses provide sensitivity to NP beyond integrated rates
- Can test presence of new mediators and different spin structures
- The differential decay rate

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

unpolarized signal fraction   polarized signal fraction

- D^* longitudinal polarization fraction as function of $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$:

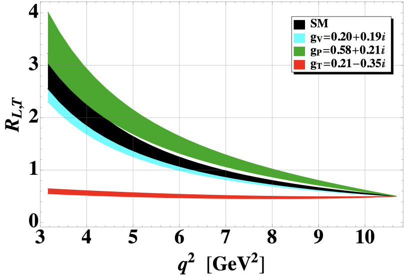
$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$



- θ_l: angle between the μ lepton direction and the direction opposite the B^0 meson, in the W^+ rest frame
- χ: angle between the plane by the D^{*-} meson and the plan formed by the W^+ decay, in the B^0 rest frame
- θ_D: angle between the direction of the D^0 meson and the direction opposite the B^0 meson, in the D^{*-} rest frame

Expected value of F_l^D

- $F_L^{D^*}$ value within the SM scenario has been predicted with different methods
- The most recent theoretical predictions are:
  - 0.441 ± 0.006 arXiv:1808.03565 *Zhuo-Ran Huang, Ying Li, Cai-Dian Lu, M. Ali Paracha, Chao Wang*
  - 0.457 ± 0.010 arXiv:1805.08222 *Srimoy Bhattacharya, Soumitra Nandi, Sunando Kumar Patra*
- Predictions for NP scenarios can be found in arXiv:1907.02257
  Damir Becirevic, Marco Fedele, Ivan Nisandzic, Andrey Tayduganovd



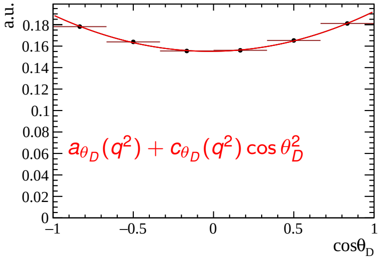
arXiv:1907.02257

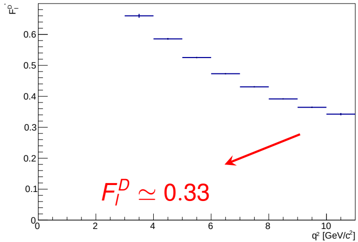
- Expected dependence of $R_{L,T}$ as function of q^2 for three NP models

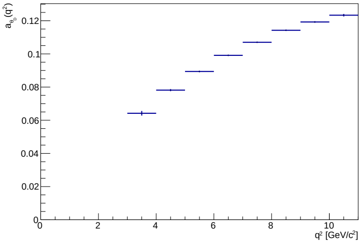
$$R_{L,T}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

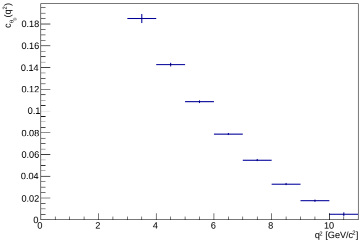
$$F_L^{D^*}(q^2) = \frac{R_{L,T}(q^2)}{1 + R_{L,T}(q^2)}$$

D^* polarization dependence on q^2 at generator level





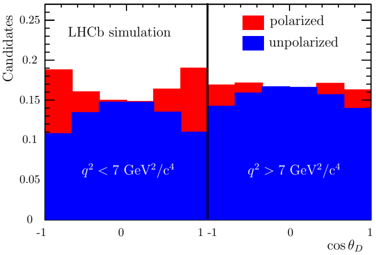




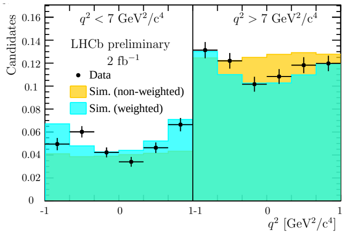
Signal & background description [*PRD 110 (2024) 092007*]

- Using Run1 and part of Run2 data (5 fb-1), same samples as for R(D*) hadronic tau analyses

- $F_L^{D^*}$ determined in two q^2 regions: $\lessgtr 7\ \text{GeV}^2/c^4$
- $F_L^{D^*}$ is extracted from $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$, determined splitting the signal sample in:
  - **unpolarized** $\Longrightarrow N_{sig}^{unpol} \propto a_{\theta_D}(q^2)$
  - **polarized** $\Longrightarrow N_{sig}^{pol} \propto c_{\theta_D}(q^2)$
- $\cos\theta_D$ signal distribution corrected for reconstruction effect



- $D^{*-}DX$ background templates determined from simulation
- Assuming no $F_L^{D^*}$ dependence on the D meson decay mode
- $\cos\theta_D$ distribution corrected through fully reconstructed control samples:
  - $D_s \rightarrow 3\pi^\pm$
  - $D^+ \rightarrow K^-2\pi^+$
  - $D^0 \rightarrow 3\pi^\pm K^-$



Extrapolation of $F_L^{D^*}$ on simulated sample *PRD 110 (2024) 092007*

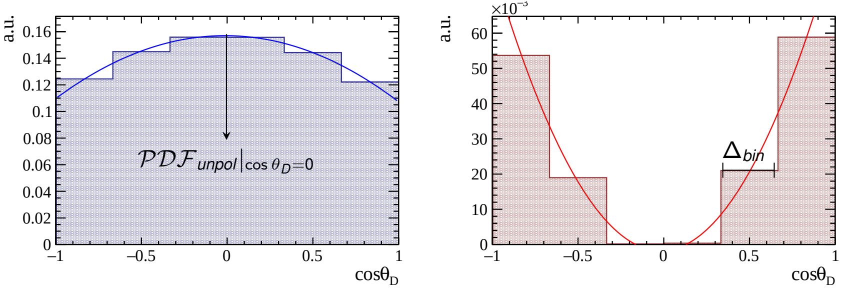
- $F_L^{D^*}$ can be determined using the equations in slide 20

$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

- a_{θ_D} and c_{θ_D} are directly related to the polarized and unpolarized yield

$$a_{\theta_D}(q^2) = N^{unpol} \cdot \mathcal{PDF}_{unpol}|_{\cos\theta_D=0}, \qquad c_{\theta_D}(q^2) = \frac{3}{2} N^{pol} \Delta_{bin}$$

signal $\cos\theta_D$ distribution



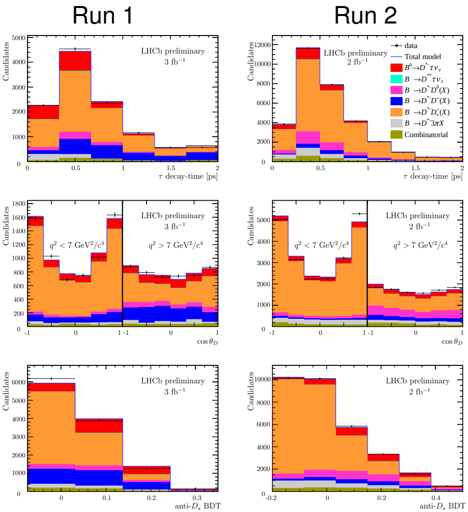
Signal fit results [*PRD 110 (2024) 092007*]

- Signal yields from a 4D-binned template fit:
  - τ^+ lifetime (first row)
  - q^2 & $\cos\theta_D$ (second row)
  - anti-D_s BDT output (third row)
- Fit performed simultaneously on Run 1 and Run 2
- Results are integrated over the two data samples

$$q^2 < 7\,\mathrm{GeV}^2/c^4: \quad 0.51 \pm 0.07(stat) \pm 0.03(syst)$$
$$q^2 > 7\,\mathrm{GeV}^2/c^4: \quad 0.35 \pm 0.08(stat) \pm 0.02(syst)$$
$$q^2\,\text{integrated}: \quad 0.43 \pm 0.06(stat) \pm 0.03(syst)$$

- All values are found to be compatible with the SM within 1σ
  - expected value in the integrated region ~ 0.44

[arXiv:1808.03565, arXiv:1805.08222, arXiv:1907.02257]



Systematic uncertainties [*PRD 110 (2024) 092007*]

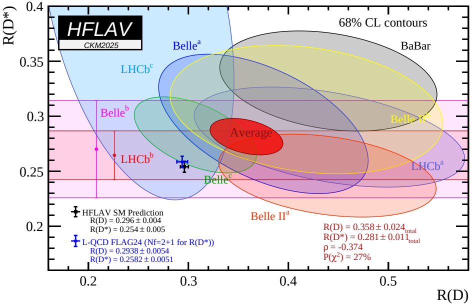
Source	low q^2	high q^2	integrated
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
TemplateSize	0.026	0.017	0.019
$\tau^+ \to 3\pi^\pm\pi^0$ fraction	0.001	0.001	0.001
D^{**} feed-down	0.001	0.004	0.003
Signal selection	0.005	0.004	0.005
Bin migration	0.008	0.006	0.007
$F_L^{D^*}$ in simulation	0.007	0.003	0.007
D_s decay model	0.008	0.009	0.009
$\cos\theta_D$ $D^{*-}D_s$	0.002	0.001	0.002
$\cos\theta_D$ $D^{*-}D_s^{*+}$	0.007	0.002	0.004
$\cos\theta_D$ $D^{*-}D_sX$	0.007	0.006	0.007
$\cos\theta_D$ $D^{*-}D^+X$	0.002	0.002	0.003
$\cos\theta_D$ $D^{*-}D^0X$	0.002	0.002	0.003
$F_L^{D^*}$ integrated	-	-	0.002
Total	0.034	0.023	0.029

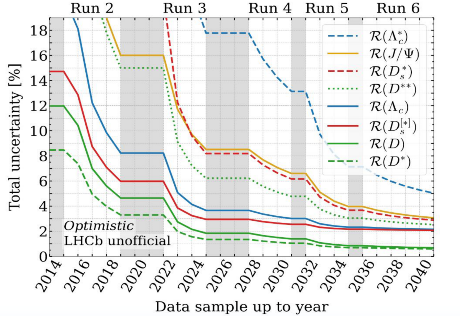
Dominant source of systematic are:

- Limited size of the simulation samples
- Form factor parameterization
- Modelling of the D_s
- $\cos\theta_D$ shape in $D^{*-}D_sX$ backgrounds
- Bin migration
- Signal acceptance
- Form factor model

Summary of the results

- Recent results from semileptoni c$B^0 \to D^{*-}\tau^+\nu_\tau$ decays
  - $R(D) - R(D^*)$ with muonic τ decays
  - $R(D^*)$ with hadronic τ decays
  - First measurement of $F_L^{D^*}$ with hadronic τ decays
- **Combined** $R(D) - R(D^*)$ is still a **3.8**σ tension from the SM
  - waiting for the publication of the new Babar result
- Stastical uncertainties expected to be reduced significantly in the near future
- The risk is to be dominated by systematic uncertainties





Dominant systematic uncertainties

Three categories, with very different scaling behaviour:

- **Simulated sample size** (template statistics)
  - dominant in $R(D^*)$ muonic, hadronic and $F_L^{D^*}$
  - reducible: fast simulation (ReDecay, tracker-only), already deployed for Run 2/3 productions
- **Physics background modelling** ($D_s \to 3\pi X$, D^{**} feed-down, double charm)
  - constrained with control samples, but external knowledge is the bottleneck
  - partially reducible: needs external inputs (BESIII, Belle II) and better theory guidance on D^{**} states
- **Signal form factors** (model + parameters)
  - enters both signal templates and acceptance corrections; handled via HAMMER reweighting
  - not purely experimental: needs theory inputs

$R(D^{**})$ measurement

$B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decay measurement [PRL 135 (2025) 021802]

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

$$D_1'(2400)^0: m = 2412 \pm 9\,\text{MeV}/c^2$$
$$\Gamma = 314 \pm 29\,\text{MeV}/c^2$$
$$D_1(2420)^0: m = 2422.1 \pm 0.6\,\text{MeV}/c^2$$
$$\Gamma = 31.3 \pm 1.9\,\text{MeV}/c^2$$
$$D_2(2460)^0: m = 2461.1 \pm 0.8\,\text{MeV}/c^2$$
$$\Gamma = 47.3 \pm 0.8\,\text{MeV}/c^2$$

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

Goals of the analysis

- Search for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays
- Measure:

$$\mathcal{B}(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau) \times \mathcal{B}(D_{1,2}^{**0} \to D^{*+}\pi^-)$$

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

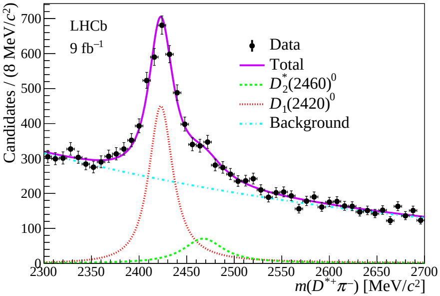
SM prediction 0.09 ± 0.02

- Measured normalised to $\mathcal{B}(B^- \to D_{1,2}^{**0} D_s^{(*)+})$ determined form $\mathcal{B}$ and amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$
- Increased statistics by combining D_s^- & D_s^{*-}

Selection of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ [PRL 135 (2025) 021802]

- Run1 & Run2 dataset $\int\mathcal{L} = 9\,\text{fb}^{-1}$, using hadronic *tau* decays
- Trigger and pre-selection requirement
- Flight distance requirement of the τ^- to suppresses prompt $B \to D^{**0}\pi^-\pi^-\pi^+(X)$
- **3 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 $m(D^{*+}\pi^-)$ without anti-D_s^+ BDT
  - Investigate components of the decay
  - Not possible to distinguish the broad $D_1'(2400)^0$ from combinatorial background

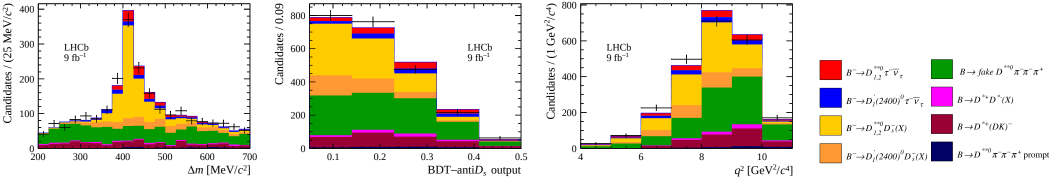
Selected mass spectrum, w/o the anti-D_s^+ BDT



3089 ± 102 $D_{1,2}^{**0}$ candidates
2456 ± 75 $D_1(2420)^0$ candidates
633 ± 69 $D_2^*(2460)^0$ candidates

- Signal extracted from binned fit to: $\Delta m = m(D^{*-}\pi^+) - m(D^{*-})$, anti-$D_s$ BDT, $q^2 = (p_B - p_{D^{**}})^2$

$B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decay measurement [PRL 135 (2025) 021802]



- $B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau$ measured with 3.5σ significance
- Branching ratio measurement: $K = \dfrac{\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^{**0}_{1,2}D_s^{(*)-})} = 0.19 \pm 0.04$

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

- LFU ratio measurement, using known $\mathcal{B}(B^- \to D^{**0}_{1,2}\mu^-\bar{\nu}_\mu)$ PRD 107 (2023) 092003

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

  in agreement with SM prediction 0.09 ± 0.02 PRD 97 (2018) 075011
- Strong evidence that the $R(D^*)$ tension is not caused by a D^{**} feed-down underestimation

- Systematic uncertainties for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decay measurement [PRL 135 (2025) 021802]

Source	Systematic uncertainty [%]
Form factors	3.7
$D_2^*(2460)^0$ fraction	4.4
Finite size of the simulated samples—efficiency	4.3
Finite size of the simulated samples—templates	4.1
Variables and binning choices	5.0
$B^- \to D^{**0}(DK)^-$ background	3.6
Selection and analysis	2.0
Detachment requirement	4.0
WS background description	2.0
Total	11.4

Analyses ongoing

$R(D^*)$ measurements

- Many analyses are on-going to improve this measurement
- Analysis strategy is more or less always the same but effort in optimizing signal selection and MVA response

Run2 data

- Update of $R(D^*)$ hadronic ($D^0 \to K\pi$) to full Run1+Run2 dataset
- New $R(D^*)$ hadronic with ($D^0 \to K3\pi$)
- Update of $R(D^0)$ and $R(D^*)$ with muonic τ decays

Run3 data

- $R(D^0)$ and $R(D^*)$ with hadronic τ decays
- Update of $R(D^*)$ hadronic with ($D^0 \to K\pi$)
- Update of $R(D^*)$ hadronic with ($D^0 \to K3\pi$)
- First measurement of $R(D^*)$ with τ/e

Angular measurements

- Wilson coefficients measurement in combined hadronic and muonic $B^0 \to D^{*-}\tau^+\nu_\tau$:
  - simultaneous fit to the LHCb data samples used in the published $R(D^*)$ with hadronic (part of Run2) and muonic (Run1) decays
  - the $F_L^{D^*}$ information is also included (Run1 + part of Run2)
  - the parameters in the fit are constrained accordingly to the $R(D^*)$ measurements
  - toy studies for fit validation in various BSM scenarios.

- Wilson coefficients measurement in muonic $B^0 \to D^{*-}\tau^+\nu_\tau$ decays using Run2 data
  - 5D template maximum likelihood fit to q^2, $\cos\theta_\ell$, $\cos\theta_D$, χ, m^2_{miss}
  - extract hadronic form factors and Wilson coefficients
  - determing also $R(D^*)$ from the fit results

- Update of $F_L^{D^*}$ measurement
  - included in the ongoing hadronic $R(D^*)$ update
  - using the same fit results of $R(D^*)$
  - $F_L^{D^*}$ determined fitting the $\cos\theta_D$ background subtracted distribution and correcting for efficiency

- Possible measurement of τ polarization
  - feasibility studies are on-going using both hadronic and muonic τ decays
  - main challange: τ-direction resolution and kinematic ambiguities; angular shape of backgrounds

Conclusions

- LHCb has established a broad $b \to c\tau\nu$ programme with $B^0 \to D^{*-}\tau^+\nu_\tau$:
  - $R(D^{(*)})$ with two independent τ tags (muonic and hadronic)
  - first measurement of $F_L^{D^*}$ in this channel
  - first evidence of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$
- Individual results compatible with the SM; the $R(D)$–$R(D^*)$ world average keeps a $\sim 3\sigma$ tension
- The form-factor treatment drives the **experimental** systematics, not only the SM predictions
- HAMMER is now standard in all analyses: from form-factor template corrections and systematics to **in-fit floating form factors**
- Next generation: relax the SM assumption by floating the **Wilson coefficients** directly in the fit, and move to full angular analyses

Question to the theory community

Beyond the observables currently under study, are there additional quantities worth measuring, and in which form should we publish our results to make them maximally reusable?