Lepton Flavour Universality tests using semileptonic b-hadron decays

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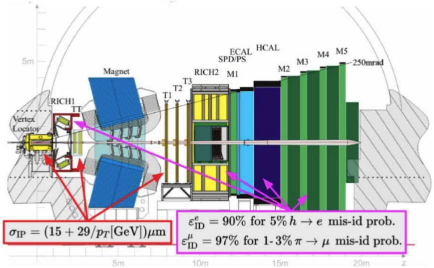
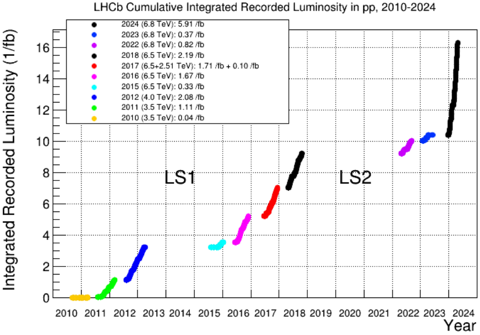
LHCb detector

Single-arm forward spectrometer:

- Designed for the heavy flavor physics with $2 < \eta < 5$ ($\sim 25\%$ *of* $b\bar{b}$ *pairs in detector acceptance*)
- Coverage is complementary to ATLAS and CMS
- Efficient trigger, excellent performance of tracking and vertexing, powerful particle identification, allow to perform high precision measurement of semileptonic B decays



Detector at Run1 - Run2 stage

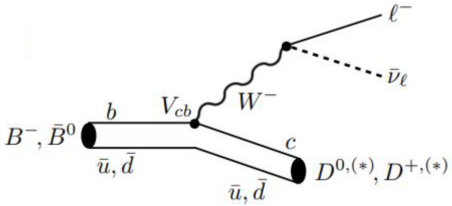


Introduction - LFU

- Semileptonic b-hadron decays provide powerful probes for testing the

Lepton Flavor Universality,

which states that the interactions of the electroweak bosons with the leptons are independent of the lepton flavor (up to explicit mass dependence in phase space and fermion helicity)



- This talk reviews recent results of LFU tests in tree level $b \to c\ell\nu$ decays at LHCb for μ and τ modes
- Studying LFU in electron mode is a work in progress in LHCb
- Another possibility to study LFU is $b \to s\ell\ell$ which is a rare decay with branching fraction $< 10^{-6}$, for more details on rare processes program on LHCb see talk by Lais Soares Lavra

$R(D^{\star})$ measurements at LHCb

- One way to test LFU is to measure ratios of branching fractions to final states with different lepton flavors ($\ell \in e, \mu$):

$$R(D^{(*)}) = \frac{Br(B^0 \to D^{(*)}\tau\nu_\tau)}{Br(B^0 \to D^{(*)}\ell\nu_\ell)}$$

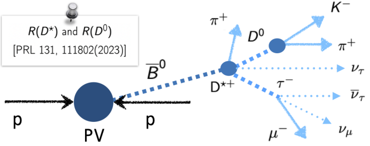
- Ratio is particularly appealing because it provides small theoretical uncertainties (cancellation of most of the form factor uncertainty) and some systematic uncertainties cancel out in ratio measurement

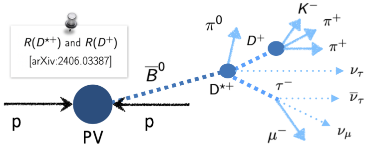
Recent results in $R(D^{(*)})$ measurements with $\ell = \mu$ on LHCb are based on two different τ reconstructed strategies :

Muonic mode $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	**Hadronic mode** $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$
• $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$ (2023) [PRL 131, 111802(2023)], supersedes [PRL 115, 111803(2015)] • $\mathcal{R}(D^{*+})$ and $\mathcal{R}(D^+)$ (2024) [arXiv:2406.03387]	• Test of lepton flavor universality using $\overline{B}^0 \to D^{*+}\tau^-\nu_\tau$ decays with hadronic τ channels [Phys. Rev. D 108, 012018] 2023, [Phys. Rev. D 109, 119902](E)(2024)]

$R(D^\star)$ measurements at LHCb

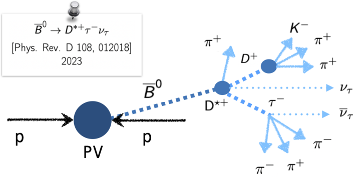
Muonic mode $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$





- Higher statistics
- Multiple missing neutrinos

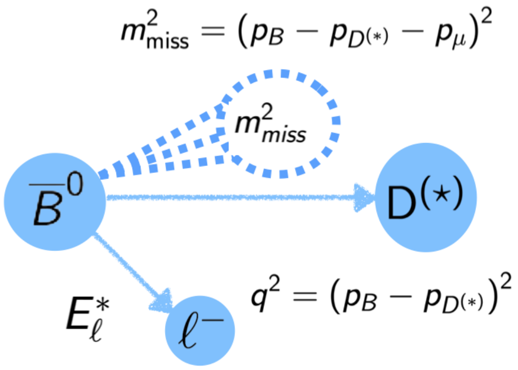
Hadronic mode $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$



- Higher purity sample (reconstructible τ decay vertex and pions with clean signature in LHCb)
- $R(D^\star)$ needs external inputs (branching fractions to normalisation and background modes)

Muonic mode $\mathcal{R}(D^{*+})$ and $\mathcal{R}(D^{0|+})$

- Many missing neutrino allow only partial reconstruction, which leaves the signal highly susceptible to a large number of backgrounds
- $\overline{B}^0 \to D^{*+}\mu^-\nu_\mu$ used as a normalisation mode
- To distinguish between signal $\overline{B}^0 \to D^{*+}\tau^-\nu_\tau$, normalisation modes and various background 3 key kinematic variables are used :
  1. E_ℓ^* spectra which is substantially different between muon and tau modes
  2. m^2_{miss} - is effective to suppress backgrounds
  3. q^2 - squared four-momentum transfer to the lepton system,

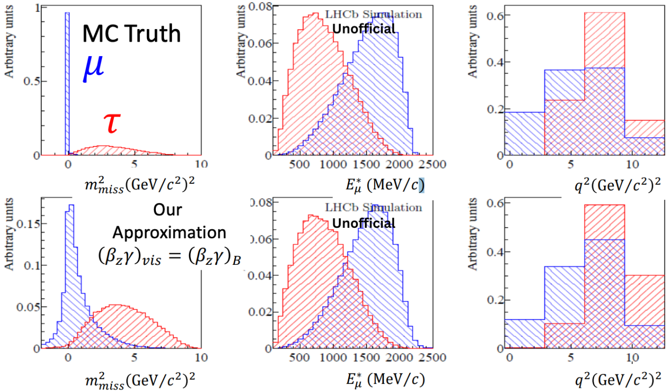


- Make measurement of $\mathcal{R}(D^{*+})$ and $\mathcal{R}(D^{0|+})$ using the same dataset.

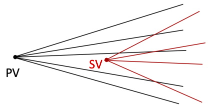
Muonic mode $\mathcal{R}(D^{*+})$ and $\mathcal{R}(D^{0|+})$ - reconstruction

- Many missing neutrino allow only partial reconstruction
- Kinematic variables in the B candidate rest frame, approximated using the velocity of the reconstructed charm-lepton system, μH_c along the beam axis z :

$$\frac{(p_B)_z}{m_B} = \frac{(p_{\mu H_c})_z}{m_{\mu H_c}}$$



- Only partially reconstructed B decay → variety of backgrounds → signal candidates need to be isolated from additional tracks in the event
- Charged isolation tool → machine-learning algorithm, scan every track and compare against $D^{\star+}\mu^-$vertex



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

- Split Run 1 dataset (3 control mode selected with isolation tool to provide constraints to backgrounds ($B \to (D^{**} \to D^*\pi)\ell\nu$ "One pion sample" ; $B \to (D^{**} \to D^*\pi\pi)\ell\nu$ - "Two pion sample" ; $B \to D^{(*)}DX$ - "Kaon sample") + signal) into two subsets :
  - $\{D^0\mu\}$ - Veto $D^{*+} \to D^0\pi^+$
  - $\{D^*\mu\}$ - Combine D^0 with slow pion
- Simultaneous 3D template fit in E^*_μ, m^2_{miss} , q^2 fit on 8 samples

$R^0_D = 0.441 \pm 0.060\,(\text{stat}) \pm 0.066\,(\text{sys})$

$R_{D^*} = 0.281 \pm 0.018\,(\text{stat}) \pm 0.023\,(\text{sys})$

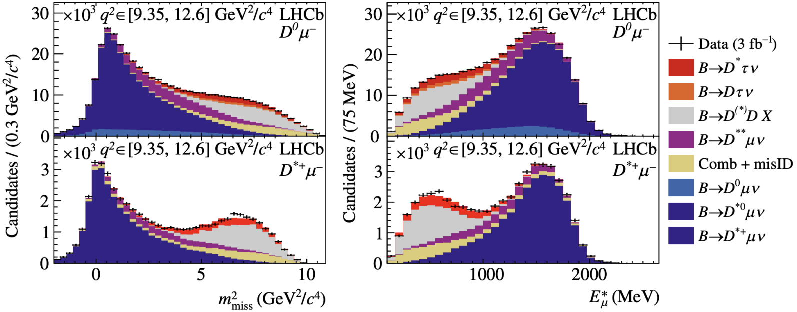
Correlation coefficient $= -0.43$

Main systematic uncertainties:

- Limited MC statistics

SM prediction [HFLAV, Phys. Rev. D 107, 052008]:

$R_{D^*} = 0.254(5)$ $R_D = 0.298(4)$



$\mathcal{R}(D^{*+})$ and $\mathcal{R}(D^{+})$ (2024) [arXiv:2406.03387]

- First measurement utilizing dedicated $B \to H_c\tau \to \mu\nu\nu\nu$ trigger lines for Run 2 (2016 data)
- First analysis that uses tracker-only simulation (x8 faster) $\to$ templates have much higher statistics

$$R_{D^{(*)+}} = \frac{\mathcal{B}(B^0 \to D^{(*)+}\mu^+\nu_\mu)}{\mathcal{B}(B^0 \to D^{(*)+}\tau^+\nu_\tau)} = \frac{\epsilon_\mu^{D^{(*)+}} \cdot N_\tau^{D^{(*)+}}}{\epsilon_\tau^{D^{(*)+}} \cdot N_\mu^{D^{(*)+}}} \cdot \frac{1}{\mathcal{B}(\tau^+ \to \mu^+\nu_\tau\bar{\nu}_\mu)}$$

$R_{D^+} = R_D = 0.249 \pm 0.043\,(\text{stat}) \pm 0.047\,(\text{sys})$

$R_{D^{*+}} = R_{D^*} = 0.402 \pm 0.081\,(\text{stat}) \pm 0.085\,(\text{sys})$

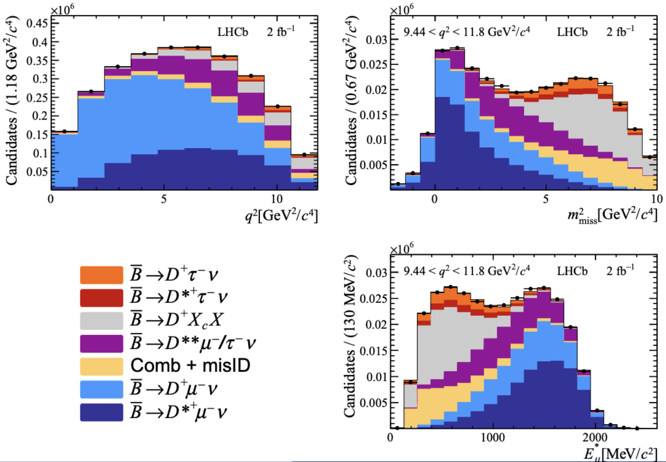
Correlation coefficient $= -0.39$

Main systematic uncertainties:

- Form factor parameterisation
- Background modeling

SM prediction [HFLAV, Phys. Rev. D 107, 052008]:

$R_{D^*} = 0.254(5)$ $R_D = 0.298(4)$



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

- Use a normalization mode, then extract $\mathcal{R}(D^*)$ using external branching fraction as input (uncertainty is lower compared to systematic if normalised directly to muonic mode)
- Background:
  - $B \to D^{*-}3\pi X$ prompt decay: $\sim 100\times$ signal. Suppressed by requiring displaced τ vertex
  - $B \to D^{*-}D(X)$ prompt decay: $\sim 10\times$ signal. Supressed by isolation requirement and BDT classifier trained on $\tau \to 3\pi X$ (anti-D_s^+ BDT)

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

From simulation

$$\kappa(D^*) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \left\{ \frac{1}{\mathcal{B}(\tau^+ \to 3\pi\nu_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\nu_\tau)} \right\}$$

External branching fractions

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

Hadronic mode $\mathcal{R}(D^*)$ and $\mathcal{R}(D)$ [Phys. Rev. D 108, 012018] 2023

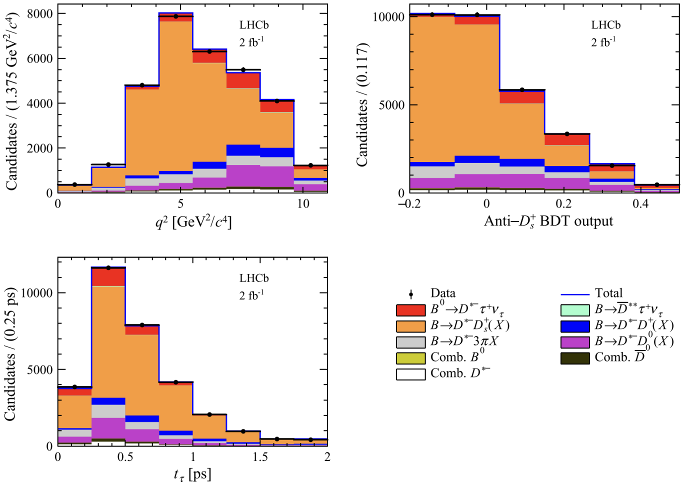
- Signal yield N_{sig}:
  - 3D binned template fit on $q^2 \equiv (p_B - p_{D^*})^2$, τ lifetime, Anti-D_s^+ BDT
- Fractions of different $D_s^+ - 3\pi X$ and $B \to D^{*-} D_s^+(X)$ controlled by fits to data enhanced with D_s^+ decays
- Normalisation yield N_{sig}:
  - Fit to $m(D^{*-}3\pi)$ in fully reconstructed sample

$R_{D^*} = 0.247 \pm 0.015\,(\text{stat}) \pm$

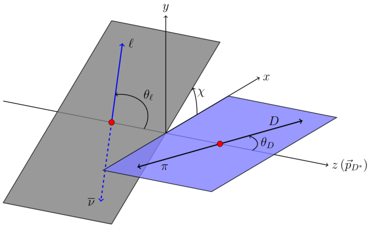
$\pm 0.015\,(\text{sys}) \pm 0.012\,(\text{ext})$

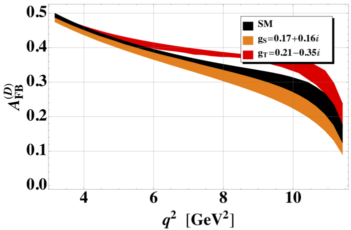
Main systematic uncertainties:

- External branching fraction
- Signal and background modeling



Other LFU measurments - angular analysis





Dependence of $A_{FB}^{D^*}$ from q^2 for SM, scalar and tensor current NP contribution [arXiv.org:1907.02257]

- New Physics (NP) can be detected in angular coefficients even if $R(D^*)$ is compatible with SM. Furthermore, NP can be characterised in the angular analysis
- Full angular differential decay rate for $\overline{B} \to D^*(\to D\pi)\ell\nu_\ell$ using $\cos\theta_\ell, \cos\theta_D$ and χ:

$$\frac{d^4\Gamma^{(\ell)}}{dq^2 d\cos(\theta_\ell) d\cos(\theta_D) d\chi} = \frac{3}{8\pi}\sum_i J_i^{(\ell)}(q^2) f_i(\cos(\theta_\ell), \cos(\theta_D), \chi)$$

Decay intrinsic structure can be characterised with angular coefficients

- Forward backward asymmetry : $A_{FB}(q^2) = \frac{3}{8}\frac{(J_{6c}+2J_{6s})}{\frac{d\Gamma}{dq^2}}$
- D^*- longitudinal polarisation : $\frac{d^2\Gamma}{dq^2\, d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$

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

Other LFU measurments - D^{*-} longitudinal polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$

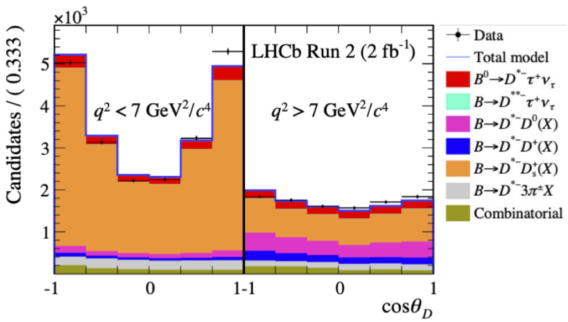
- Many different strategies are implemented for ongoing analyses in LHCb : directly fit for Wilson Coefficients in a particular FF parameterisation or measure angular coefficients in a model independent way
- In a simplified model only $D^\star$ longitudinal polarisation can be measured in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays in hadronic mode [arXiv:2311.05224] based on Run 1 + 2015,2016 statistics

- $F_L^{D^*}$ determined using a 4D binned template fit
  - $cos(\theta_D), \tau^+ lifetime$, anti-$D_s^+$, BDT, q^2

$q^2 < 7\,\mathrm{GeV}^2/c^4$: $0.51 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$

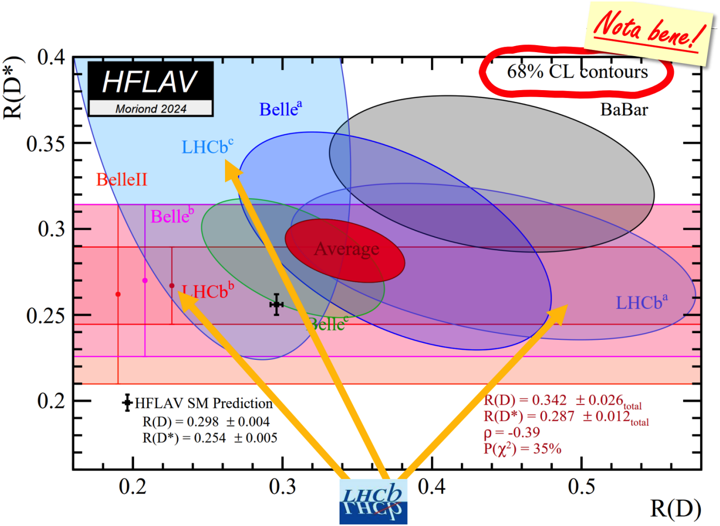
$q^2 > 7\,\mathrm{GeV}^2/c^4$: $0.35 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$

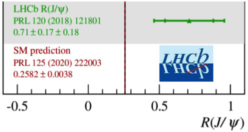
q^2integrated : $0.43 \pm 0.06\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$

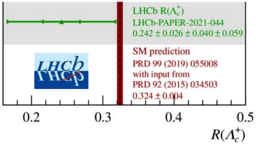


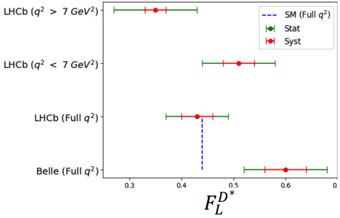
- Results compatible with the Belle result and SM [arXiv:1903.03102, Phys.Rev.D 98 (2018) 9, 095018, Eur.Phys.J.C 79 (2019) 3, 268,

LFU tests results



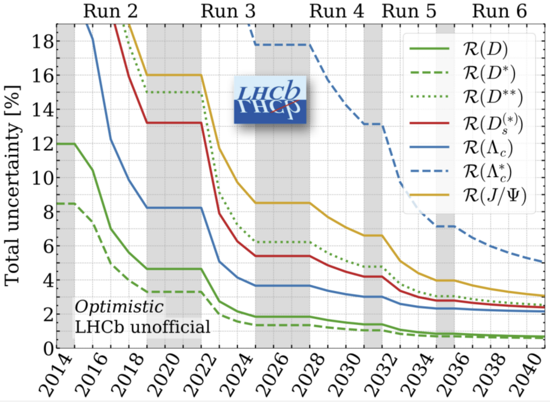






Conclusion and outlook

- Two new LHCb results of R_D and R_{D^*} in muonic mode, the most precise measurement of R_{D^*} in hadronic mode - > the discrepancy for $R(D) - R(D^*)$ with the SM is still on the 3σ level (currently 3.3σ)
  - A New fast simulation technique and improved background modeling are implemented
- First LHCb measurement of D^*- longitudinal polarisation
  - Compatible with the Belle result and SM prediction
- Angular observables are very promising for resolving potential New Physics structure
- With Run 3 underway $\rightarrow$ uncertainty improvement are expected

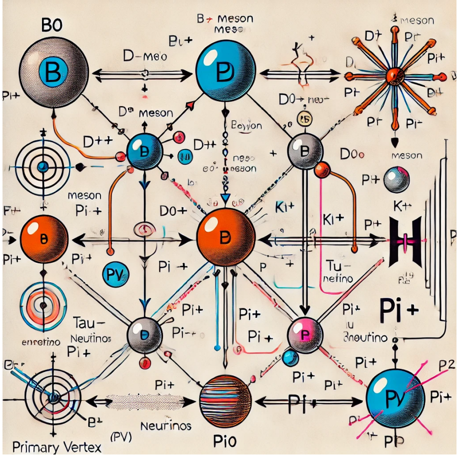


Data sample up to year
[Rev. Mod. Phys. 94, 015003 (2022)]

Conclusion and outlook

Exciting new LFU measurements are on the way—stay tuned!

Thank you!



New physics in semileptonic decays of B meson found at LHCb by DALL · E 2 AI image generation model