Measurement of semitauonic b-hadron decays

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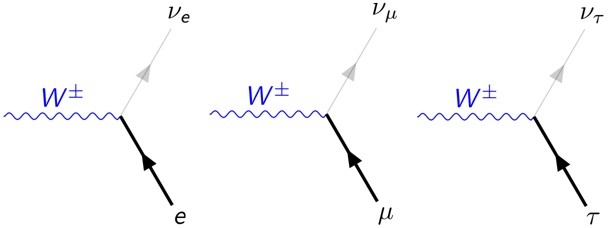
On behalf of the LHCb collaboration

Outline

Introduction

Semileptonic b-hadron decays provide powerful probes for testing the Standard Model(SM) and search for BSM effects

Lepton Flavour Universality (LFU) hypothesis: equal gauge bosons couplings to leptons



- Simple description with a tree level diagram in the SM

Tensions in complementary lepton universality tests using rare B decays ▸ more details M. McCann talk at EPS

Other measurements with semi-leptonic decays - ▸ more details A. Lupato talk at EPS

$b \to c l \nu$ transitions at the LHCb experiment

- Ratios of branching fractions is one choice to test LFU

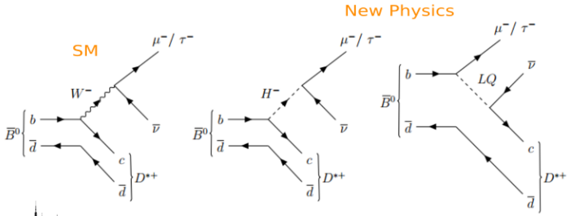
$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \nu)}{\mathcal{B}(H_b \to H_c \mu \nu)}$$

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

$$H_c = D^*, D^+, D_s, \Lambda_c^0, J/\Psi$$

- Neutrinos not detected at LHCb: approximation needed to reconstruct the B momentum
- τ decay modes used: $\tau^- \to \mu^- \nu_\mu \nu_\tau$ and $\tau^- \to \pi^+ \pi^- \pi^- \nu_\tau$

Any discrepancy could be a clear sign of New Physics (NP)

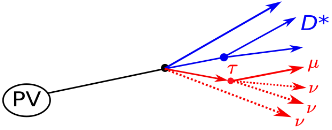


PRD 94, 034001

PRD 90, 074013

PRD 87, 014014

$\mathcal{R}(D^*)$ with $\tau \to \mu\nu\nu$



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

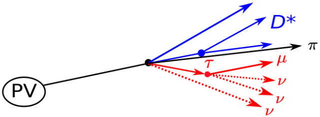
- Discriminating kinematic variables are:
  - the muon energy E_μ
  - $m^2_{miss} = (p_B - p_{D^*} - p_l)^2$
  - $q^2 = (p_B - p_{D^*})^2$

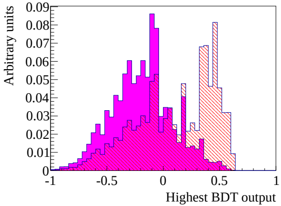
▸ PRL 115 111803

- B momentum approximated with the relation:

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

- Isolation: reject backgrounds with additional charged tracks





$\mathcal{R}(D^*)$ with $\tau \to \mu\nu\nu$

Main background contributions:

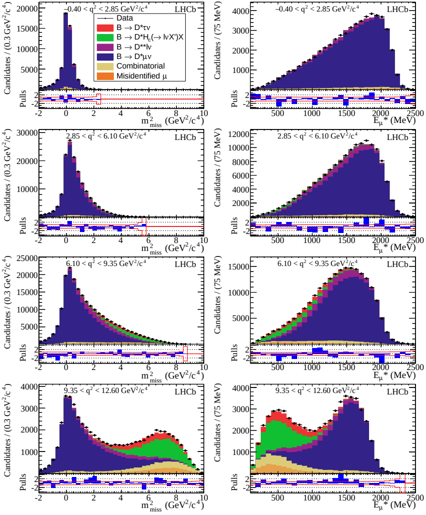
- $B \to D^{**}\mu\nu$
- $B_s \to D_s\mu\nu$
- Semileptonic decays to heavier charmed hadrons decaying to $D^{**} \to D^{*+}\pi\pi$
- $B \to D^{**}\tau\nu$
- $B \to D^{*+}H_cX$
- Hadrons(π, K, p) misidentified as muons
- Combinatorial backgrounds - wrong-sign final state combinations

Fitting strategy:

- Binned maximum likelihood method with three dimensional templates representing the signal, the normalization and the background sources
- The fit extracts the relative contributions of signal and normalization modes and their form factors

PRL 115 111803

$\mathcal{R}(D^*)$ with $\tau \to \mu\nu\nu$



$$\mathcal{R}(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$$

Dominant systematics:

- Statistical uncertainty of the simulated samples
- Backgrounds from hadrons misidentified as muons

2.1 σ greater than the SM expectation: 0.252 ± 0.003

PRD 85(2012) 094025

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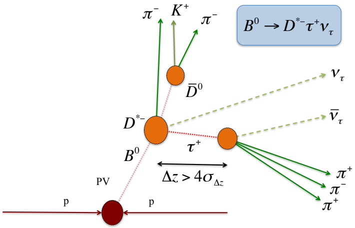
$\mathcal{R}(D^*)$ with $\tau \to \pi\pi\pi\nu$



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

- $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ is taken as normalization

$$\kappa(D^*) = \frac{\mathcal{B}(B \to D^* \tau\nu)}{\mathcal{B}(B \to D^{*-} 3\pi)}$$

$$\mathcal{R}(D^*) = \kappa(D^*) \frac{\mathcal{B}(B \to D^* 3\pi)}{\mathcal{B}(B \to D^* \mu\nu)}$$

B and τ momentum approximated by looking at the two solutions approach ▸ PRD 97, 072013

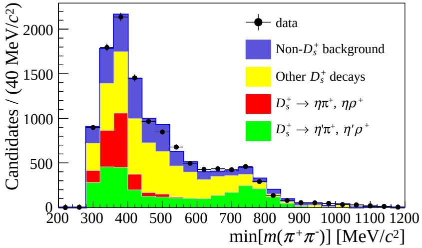
Main background contributions:

- $B \to D^{*-}3\pi X$ - 3π detached-vertex requirement
- Double charm backgrounds ($B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$) - suppression via MVA(BDT)

▸ PRL 120, 171802

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$

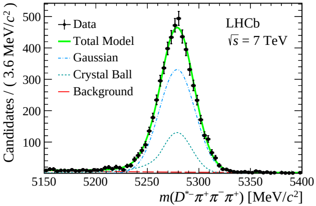
- Backgrounds from D_s^+ are determined from a fit to data
- Simultaneous fit to the invariant masses of: oppositely charged pions, same-charge pion pair and the 3π system



Signal extraction:

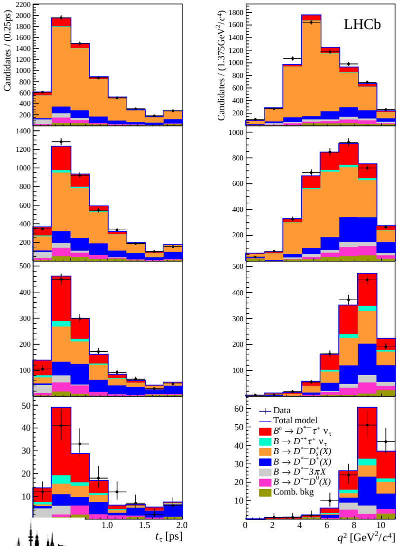
- q^2, τ decay time and BDT used as discriminating variables
- Fitting strategy: binned fit to q^2, τ decay time and BDT

Normalization extraction:



PRL 120, 171802

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$



$\mathcal{R}(D^*) = 0.280 \pm 0.018(\textit{stat}) \pm 0.029(\textit{syst})$

Dominant systematics:

- Modeling of different background sources
- MC statistics of templates
- $B \to D^*\tau\nu$ form factors
- τ polarization effects
- Possible contributions from other τ decay modes

1 σ higher than the SM prediction

PRL 120, 171802

$\mathcal{R}(J/\Psi)$ with $\tau \rightarrow \mu\nu\nu$

$$\mathcal{R}(J/\Psi) = \frac{\mathcal{B}(B_c \rightarrow J/\Psi\tau\nu)}{\mathcal{B}(B_c \rightarrow J/\Psi\mu\nu)}$$

- First study of the semitauonic decay $B_c \rightarrow J/\Psi\tau\nu$
- FFs determined directly from data
- Recent FF predictions from theory: arXiv: 2007.06956 arXiv: 2007.06957

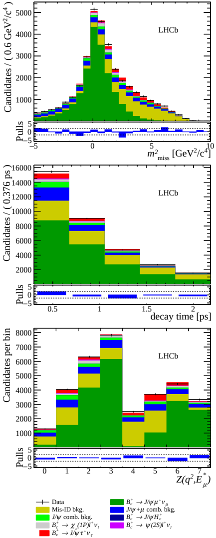
Main backgrounds:

- $B_c \rightarrow H_c X$ - modeled using a cocktail of two-body decays that proceed through excited D_s
- Combinatorial background from $B_{u,d,s} \rightarrow J/\Psi X$
- Pairs of muons to form a J/Ψ
- mis-ID - π or K is misidentified as a μ

Fit strategy: binned fit to the m^2_{miss}, B_c decay time and the quantity Z

- Z contains 8 bins in E_μ and q^2 (first 4 bins with $q^2 < 7.14\ \mathrm{GeV}^2$, the rest $q^2 > 7.14\ \mathrm{GeV}^2$)

$\mathcal{R}(J/\Psi)$ with $\tau \to \mu\nu\nu$



$$\mathcal{R}(J/\Psi) = 0.71 \pm 0.17(stat) \pm 0.18(syst)$$

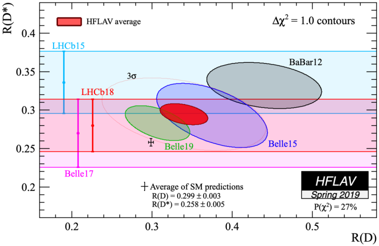
Main systematics:

- $B_c \to J/\Psi$ form factors
- Z binning strategy
- mis-ID and combinatorial backgrounds

2 σ higher than the SM prediction

PRL 120, 121801

Future prospects and ongoing analyses



- 3 σ tension with the SM prediction
- LHCb contribution with $R(D^*)$ - muonic and hadronic and $R(J/\Psi)$

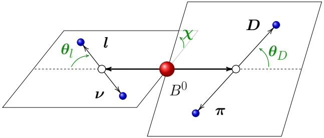
Analyses in progress (Run 1 and Run 2 data):

- $\mathcal{R}(D^+)$
- $\mathcal{R}(D^*)$ - (electron - muon)
- Combined measurement $\mathcal{R}(D^*)$ - $\mathcal{R}(D^0)$
- $\mathcal{R}(D^{**})$
- $\mathcal{R}(D_s^*)$
- $\mathcal{R}(J/\Psi)$
- $\mathcal{R}(\Lambda_c^*)$

Future prospects and ongoing analyses

Angular analyses:

- Angles feature the decay rate and are sensitive to NP

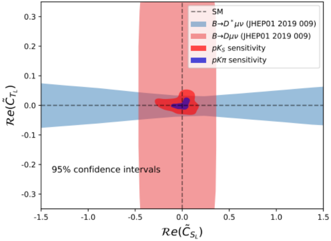


- Study potential NP scenarios and their sensitivity
- $B \to D^* \mu(\tau)\nu$ - hadronic and muonic
- $\Lambda_b \to \Lambda_c \mu\nu$ ▸ JHEP 12 148(2019)

- Operators with unknown coupling constants can be written in an effective Hamiltonian

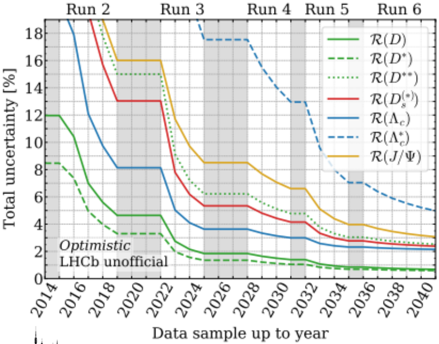
$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \sum C_i O_i$$

$$C_i = C_i^{SM} + C_i^{NP}$$



Summary

- Semileptonic decays can give us hints towards BSM physics
- LHCb has performed several LFU measurements with Run 1 data
- Ongoing analyses make use of Run 2 data measuring ratios and exploiting the angular structure of the decays
- Run 3 data-taking period from 2022 - systematic uncertainties at LHCb to scale with the accumulated sample size



arXiv:2101.08326

arXiv:1808.08865

Thank you!

BACKUP

$\mathcal{R}(D^*)$ with $\tau \to \mu\nu\nu$ systematic uncertainties

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

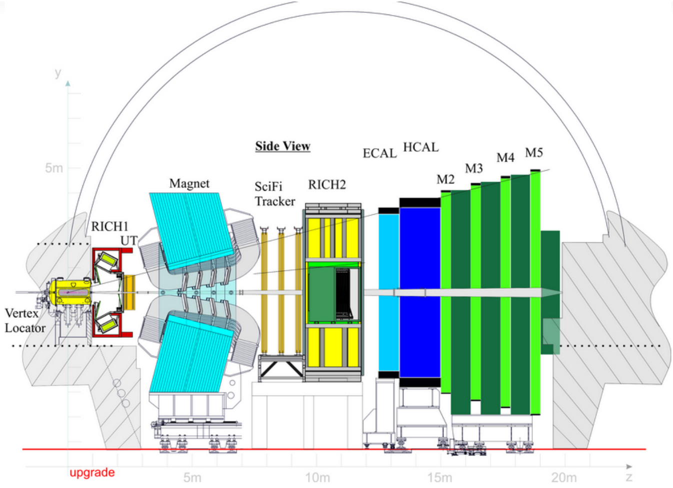
$\mathcal{R}(D^*)$ with $\tau \to \pi\pi\pi\nu$ systematic uncertainties

Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\ \tau\ \ \nu$ and $D_s^{**}\ \tau\ \ \nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-} D_s^+ X$, $B \to D^{*-} D^+ X$, $B \to D^{*-} D^0 X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-} 3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-} 3\pi$)	2.0
Total uncertainty	9.1

$\mathcal{R}(J/\Psi)$ with $\tau\to\mu\nu\nu$ systematic uncertainties

Source of uncertainty	**Size ($\times 10^{-2}$)**
Limited size of simulation samples	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau)$	0.2
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

LHCb upgraded detector



LHCb upgrade prospects