

Anomalies in $b \rightarrow c\tau\nu$ transitions at LHCb

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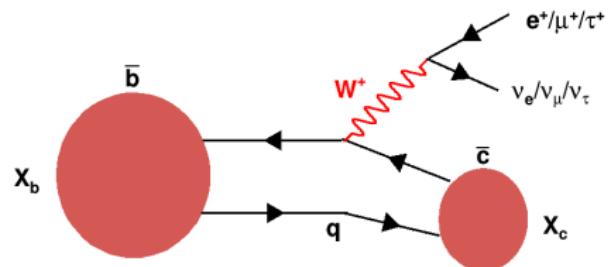
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Lepton flavour universality

- SM is Lepton flavour universal
 - Electroweak couplings to all charged leptons are universal
 - Difference between e, μ and τ driven only by mass
- LFU tests with ratios of branching fractions of decays involving different $\ell = e, \mu, \tau$

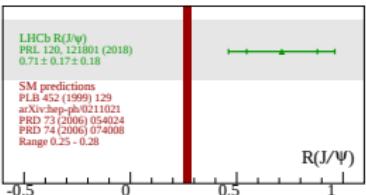
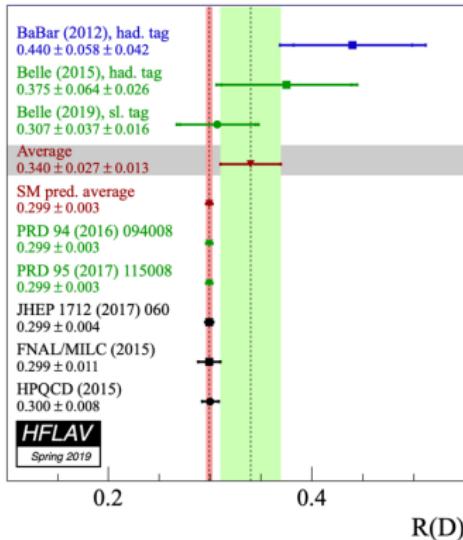
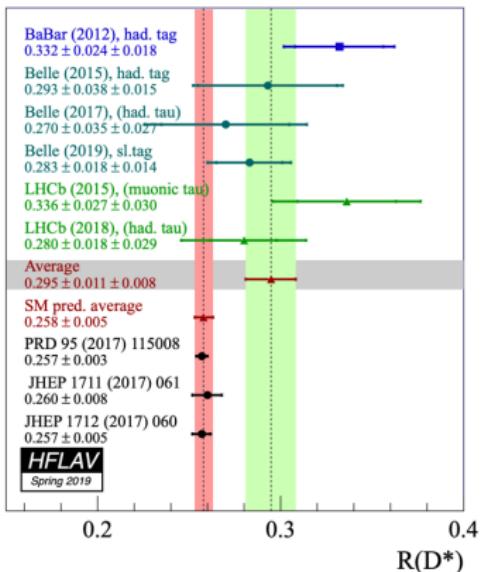
- In $b \rightarrow c$ transitions:

$$R(X_c) = \frac{\mathcal{B}(X_b \rightarrow X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \rightarrow X_c \ell \nu_\ell)}$$



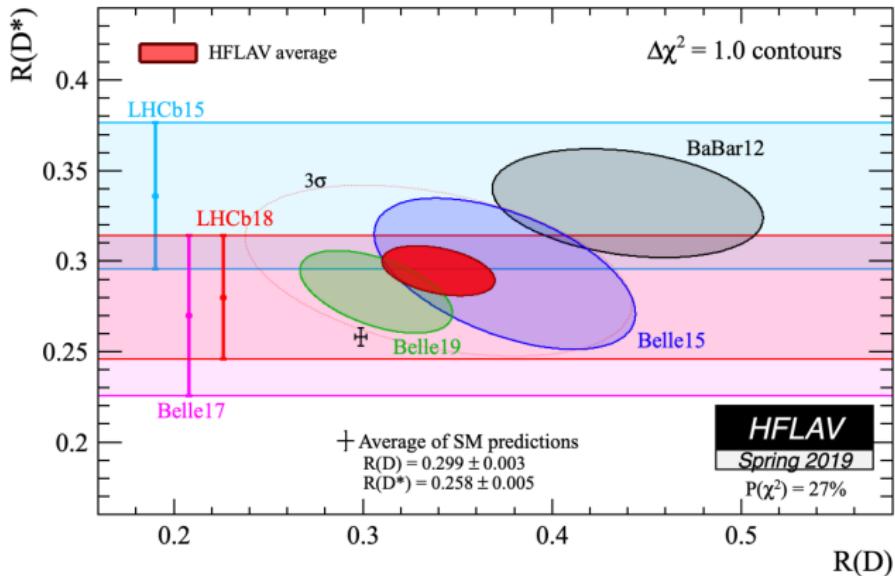
- Uncertainties related to Form Factor normalizations *mostly* cancel in the ratio
- Ratios sensitive to possible enhanced coupling to the 3rd generation (e.g. Leptoquarks) predicted by some NP models

$R(X_c)$ measurements



- All $R(X_c)$ measurements so far have central values above SM expectation

$R(D) - R(D^*)$



- Combination of $R(D)$ and $R(D^*)$ is 3.1σ from SM
 - increase to 3.8σ** with latest SM prediction from LCSR + LQCD + UB + HQET

[M. Bordone, N. Gubernari, M. Jung, D. van Dyk, EPJC **80**, 347 (2020), 1912.09335]

$R(X_c)$ measurements at LHCb

- LHCb Run 1 data - 3 fb^{-1} , 2011-12
- Measurements with **muonic** τ decays

$$R(X_c) = \frac{\mathcal{B}(X_b \rightarrow X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \rightarrow X_c \mu^+ \nu_\mu)}.$$

- Same visible final state $X_c \mu^+$
- 3D binned template fit to q^2 , m_{miss}^2 , $E_{\mu^+}^*$ and B_c^+ decay time for $R(J/\psi)$

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

PRL 115, 112001 (2015)

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

PRL 120, 121801 (2018)

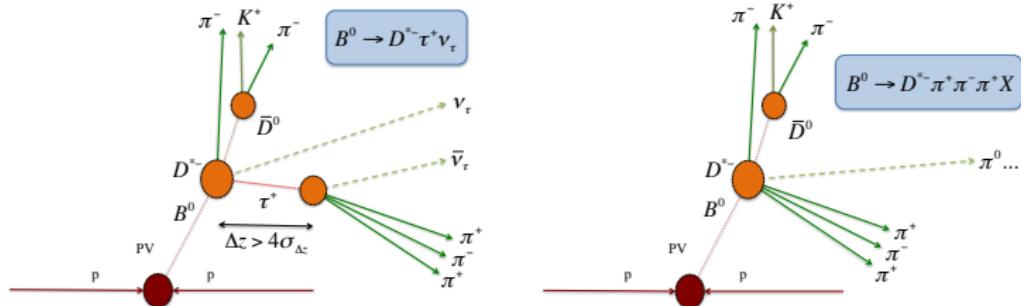
- Measurements with **hadronic** τ decays
 - $R(D^*)$ using 3-prong PRL 120, 171802 (2018), PRD 97, 072013 (2018)
 - Details in this talk

$R(D^*)$ measurement with hadronic τ decays

- Using $\tau^+ \rightarrow 3\pi^\pm(\pi^0)\bar{\nu}_\tau$ in $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ decays and measure:

$$R(D^*) = \mathcal{K}(D^*) \frac{\mathcal{B}(B^0 \rightarrow D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \rightarrow D^{*-}\ell\nu_\ell)} \quad \mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-}3\pi^\pm)}$$

- Same visible final state for the normalization mode $B^0 \rightarrow D^{*-}3\pi^\pm$
- Make use of $3\pi^\pm$ vertex



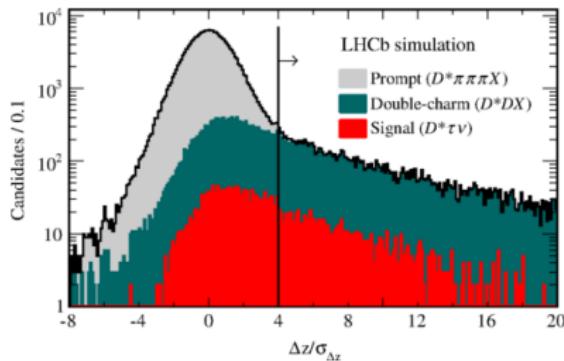
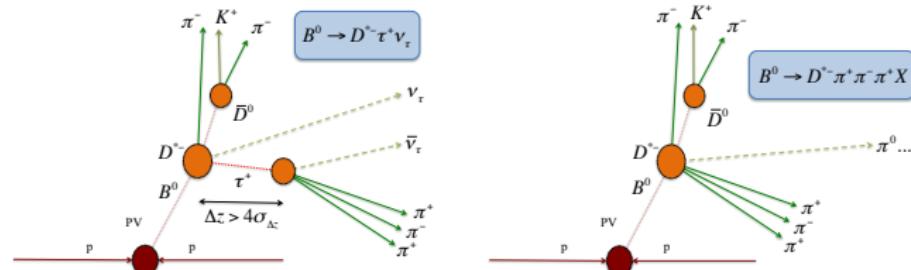
How do we measure $R(D^*)$?

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^+ \rightarrow 3\pi^\pm (\pi^0) \bar{\nu}_\tau)}$$

- N_{sig} from 3D binned template fit:
 - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
 - τ^+ decay time,
 - Output of BDT trained to discriminate τ from D_s^+ .
- Efficiencies ε from MC
- N_{norm} from unbinned fit to $m(D^{*-} 3\pi^\pm)$.
- $\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)$ and $\mathcal{B}(B^0 \rightarrow D^{*-} \ell \nu_\ell)$ are external inputs

Backgrounds - $X_b \rightarrow D^{*-} 3\pi^\pm X$

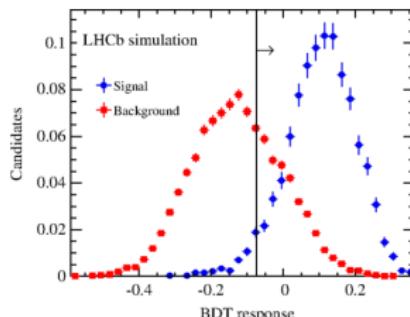
- $3\pi^\pm$ directly from the B^0



- Suppressed by requiring the τ vertex to be downstream w.r.t B vertex along the beam direction
- $\Delta z > 4\sigma_{\Delta z}$ improves S/B by 160

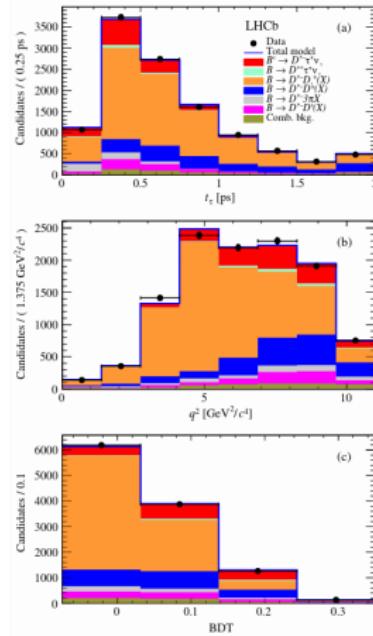
Backgrounds - $X_b \rightarrow D^{*-}D(X)$

- Double-charm decays that mimic the same final state (have non-negligible lifetime)
 - $X_b \rightarrow D^{*-}D_s^+X$
 - $X_b \rightarrow D^{*-}D^+X$
 - $X_b \rightarrow D^{*-}D^0X$
- Charged isolation algorithm to remove extra tracks forming good vertices with the signal candidate tracks
- Neutral isolation algorithm to suppress background candidates from decays with additional neutral particles
- Particle identification requirements
- A Boosted Decision Tree based on kinematics, resonant structure and neutral isolation



$R(D^*)$ result

- A 3D binned template fit to extract the signal yield
 - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
 - τ^+ decay time,
 - Output of BDT trained to discriminate τ from D_s^+ .
- Templates selected from simulation and data control samples
- $N(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = 1296 \pm 86$



$$R(D^*) = 0.280 \pm 0.018(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})^*$$

Latest value after rescaling the updated value of $\mathcal{B}(B^0 \rightarrow D^{-} \ell \nu_\ell)$

Updating $R(D^*)$ with 2015-16 data at LHCb

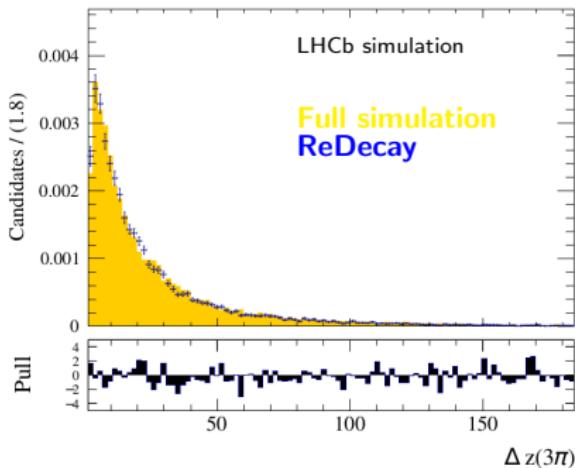
- The Run 1 measurement is systematically dominated

Source	$\frac{\delta R(D^*)}{R(D^*)}$ (%)	Future
Simulated sample size	4.7	More MC
Empty bins in templates	1.3	
Signal decay model	1.8	
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feed-downs	2.7	Measure $R(D^{**})$
$D_s^+ \rightarrow 3\pi X$ decay model	2.5	
$B \rightarrow D^{*-} D_s^+ X, D^{*-} D^+ X, D^{*-} D^0 X$ bkg	3.9	Scales with stat
Combinatorial bkg	0.7	
$B \rightarrow D^{*-} 3\pi X$ bkg	2.8	Improve selection
Efficiency ratio	3.9	Scales with stat
Normalization channel efficiency	2.0	
Total systematic uncertainty	9.1	

- The aim is to reduce the stat as well as syst uncertainty on $R(D^*)$

Strategies for improvement

- Use fast simulation (ReDecay) to produce more MC
 - 10–20 times faster [D. Müller *et al.* EPJC **78**, 1009 (2018)]
 - But one caveat - Poisson errors not applicable



- Improved charged track isolation using BDT - reduces double charm bkg
- Improved selection to remove $B \rightarrow D^*-3\pi X$ events
- Efforts to measure $R(D^{**})$ underway - well advanced

Summary and prospects

- Three $b \rightarrow c\tau\nu$ tests of LFU so far in LHCb: $R(D^*)$ muonic, $R(D^*)$ hadronic and $R(J/\psi)$ muonic
- A **3.8σ** tension in $R(D) - R(D^*)$, when combining the measurements from BaBar, Belle and LHCb
- The update of measurements at LHCb with Run 2 will bring a factor 5 in statistics.
 - Analyses ongoing with Run 2, some in advanced stage
- Many new measurements underway :
 - $b \rightarrow c\tau\nu$: $R(D^+)$, $R(D^0)$, $R(D_s^{(*)})$, $R(\Lambda_c^{(*)})$, ...
- Exploring new observables beyond the branching fraction ratios, e.g. angular observables to determine spin structure of potential NP
- Interesting times ahead!

thank you!

Back up slides

