Tests of lepton universality with semitauonic b-quark decays

BEACH 2018, Peniche

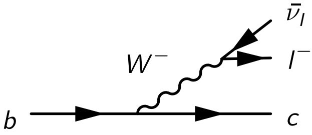
Mark Smith on behalf of the LHCb collaboration

19 June 2018

Lepton Universality

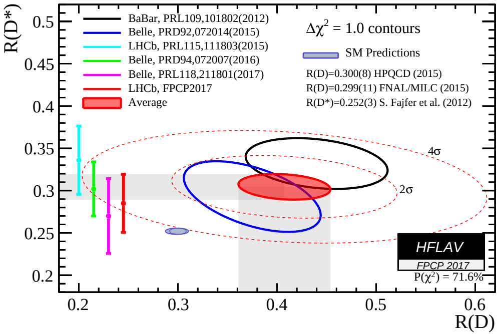
SM CC:

$$\mathcal{L}_C = \frac{-g}{\sqrt{2}}[\bar{u}_i\gamma^\mu \frac{1-\gamma^5}{2} V_{ij}^{CKM} d_j + \bar{\nu}_i\gamma^\mu \frac{1-\gamma^5}{2} e_i]W_\mu^+ + h.c.$$



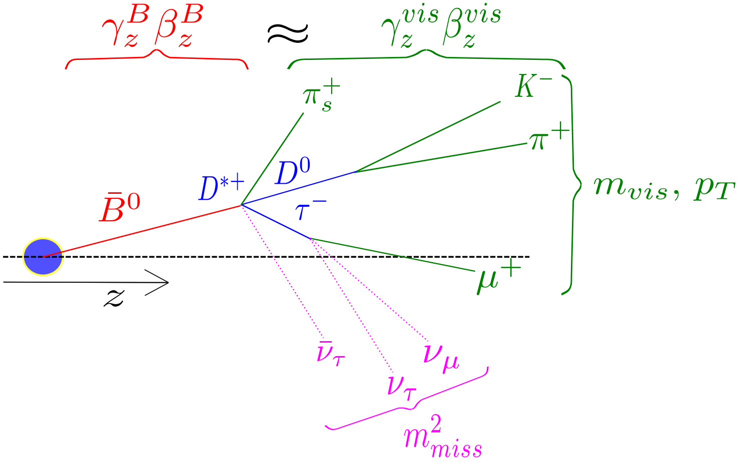
Compare μ and τ modes of semi-leptonic decays:

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



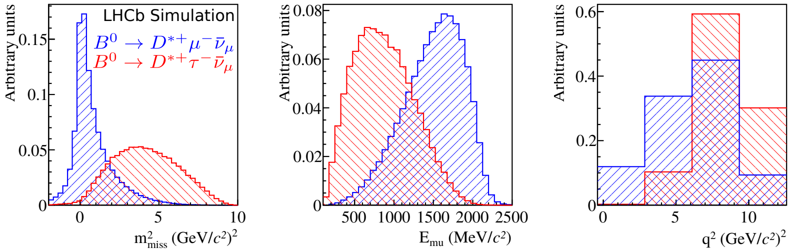
Tension with SM in $R(D)$ vs $R(D^*) \sim 4\,\sigma \to$ new physics at tree-level?

τ reconstruction : $\tau^+ \to \mu^+ \overline{\nu}_\tau \nu_\mu$ (17.4%)

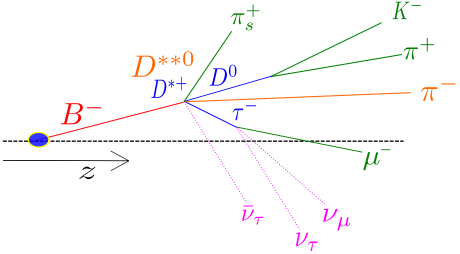


Variable	Definition	μ	τ
m^2_{miss}	$(p_B - p_{vis})^2$	peaks at 0	> 0
q^2	$(p_B - p_{D^*})^2$	$0\,\mathrm{MeV} < q^2 < 3270\,\mathrm{MeV}$	$m_\tau < q^2 < 3270\,\mathrm{MeV}$
E^*_μ	E_μ in B frame	hard	soft

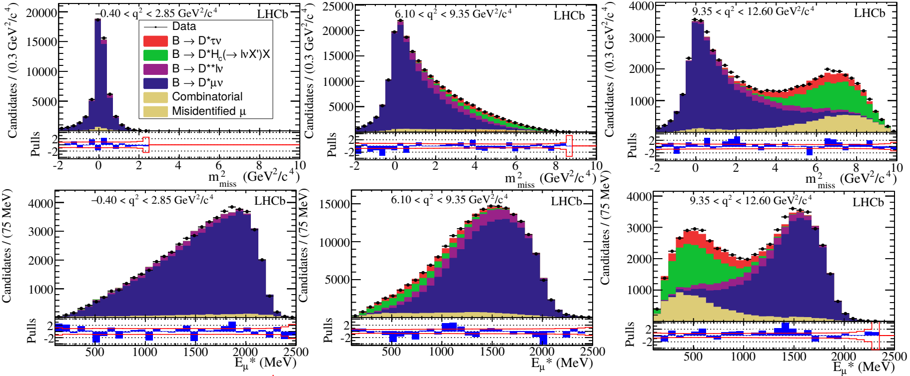
Muonic $R(D^*)$ method



- 3D template fit.
  - μ mis-ID and combinatorial taken from data.
  - All other templates from simulation with systematic variations.
- Major backgrounds:
  - $B \to D^{**}\mu\nu$
  - $B \to D^{*+}X_c$, $X_c \to X\mu\nu$
  - Reduce with charged isolation.



Run 1, 3 fb^{-1}:



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

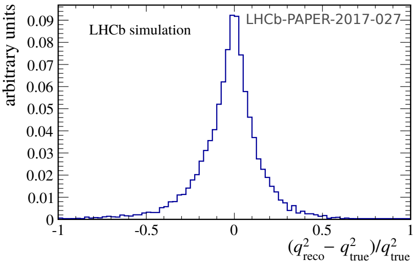
2.1 σ deviation from SM prediction

Major systematics:

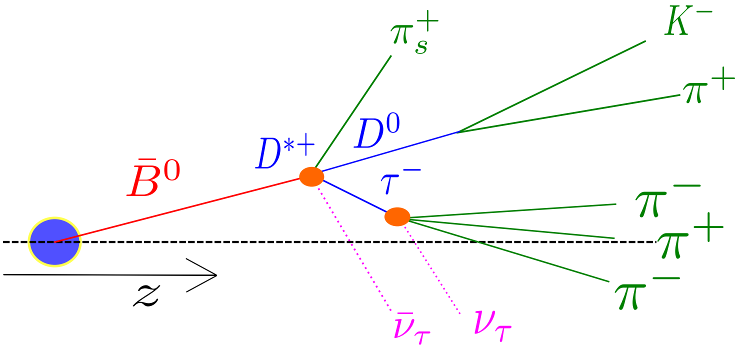
- Simulation sample size $\rightarrow$ reducable
- mis-ID sample size $\rightarrow$ reducable
- $B \rightarrow D^* \tau \nu$ form-factor $\rightarrow$ tricky

τ reconstruction : $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau(\pi^0)$ (13.9%)

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

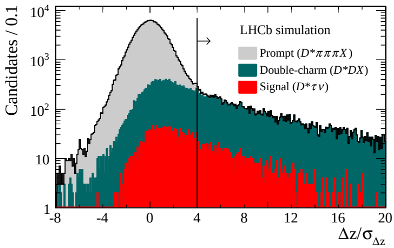


- Require external input to turn $K(D^*)$ into $R(D^*)$.
- Reconstructable τ decay vertex $\to$ background reduction!
- Estimate B kinematics (backup).

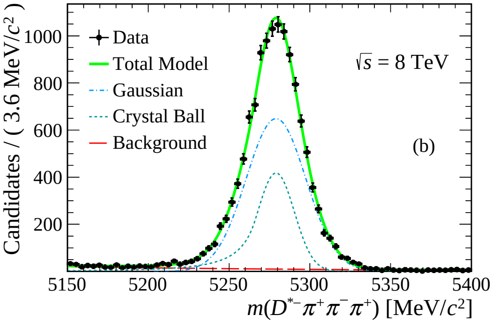


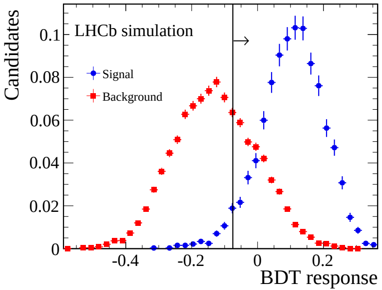
Major backgrounds:

- $B \to D^{*+}\pi^+\pi^-\pi^- X$.
  - Reduced with τ flight distance cut.
- $B \to D^{*+} X_c$
  - $X_c \to \pi^+\pi^-\pi^- X$.
  - Reduced with a multivariate discriminator.



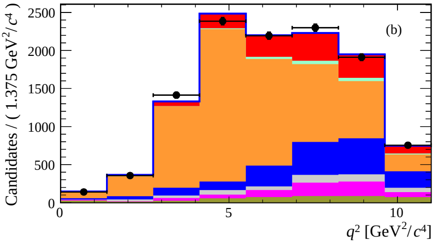
Normalisation fit to $m(D^{*+}3\pi)$:

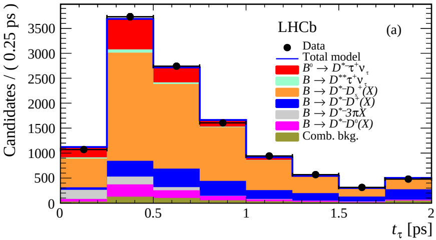




Hadronic $R(D^*)$- II

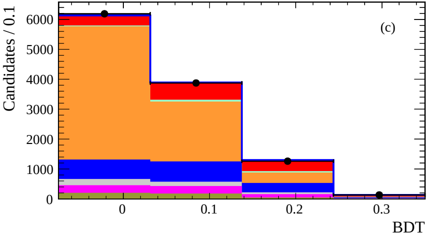
Run 1, $3\,\text{fb}^{-1}$. Fit q^2, t_τ, BDT classifier:





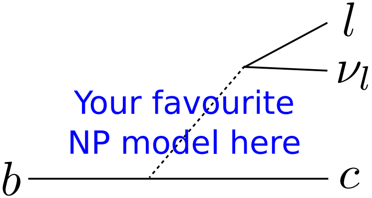
Systematics:

- Simulation sample size
- Double charm background
- $D^{*-}3\pi X$ background
- $D^{**}\tau\nu_\tau$ feed-down



$$R(D^{*-}) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(BR)$$

What else to measure?



More $b \to c$:

- $\bar{B}_s^0 \to D_s^- \tau^+ \nu_\tau$
- $B_c^+ \to J/\psi \tau^+ \nu_\tau$
- $B \to D^{**} \tau^+ \nu_\tau$ (arXiv:1606.09300)
- Lower statistics
- Theoretically studied

Baryons:

- $\Lambda_b^+ \to \Lambda_c^{(*)} \tau^+ \nu_\tau$
- Decent statistics
- Theoretically challenged

$b \to u$ transitions:

- Probe flavour structure
- $\Lambda_b^0 \to p \tau^+ \nu_\tau$
- $B^+ \to \rho^0 \tau^+ \nu_\tau$
- $B^+ \to p\bar{p} \tau^+ \nu_\tau$
- Statistically challenged
- Theoretically challenged

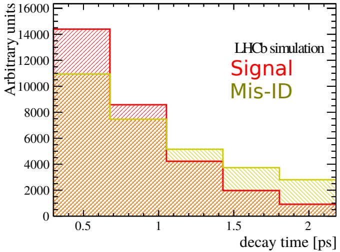
$R(J/\psi)$ PRL 120, 121801 (2018)

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} \qquad \tau^+ \to \mu^+\overline{\nu}_\tau\nu_\mu$$

- Probing same physics as $R(D^*)$. SM expectation $0.25-0.28$.
  Phys. Lett. B452 (1999) 129, arXiv:hep-ph/0211021,
  Phys. Rev. D73 (2006) 054024, Phys. Rev. D74 (2006) 074008
- Only available at LHCb.

As per $R(D^*)$ use kinematic distributions: m^2_{miss}, $Z(q^2, E^2_\mu)$.

- Additionally consider B_c^+ decay-time.
- $B_c^+ \to J/\psi$ form-factors are unkown - estimated from fit to enriched sample of the normalisation mode.

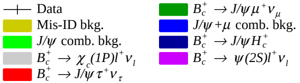


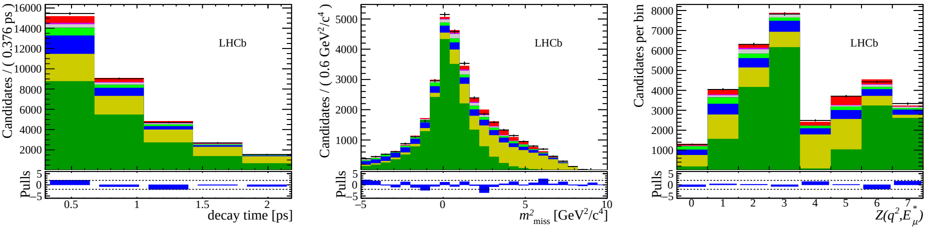
$R(J/\psi)$ results PRL 120, 121801 (2018)

3D template fit: B_c decay-time, m^2_{miss}, Z.

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

- Compatible with SM at $2\,\sigma$.
- First evidence of decay $B_c^+ \to J/\psi\,\tau^+\nu_\tau$
- Largest systematics from $B_c \to J/\psi$ form-factor and limited simulation sample size - both can be improved.
- Lattice form-factor calculation is on the way - see here





Looking forward

7 - 8 TeV | 13 TeV | 14 TeV | HL-LHC →

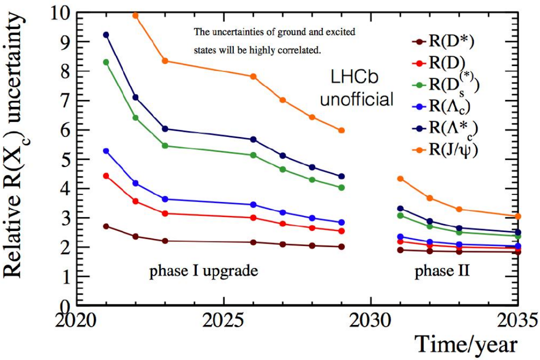
Run 1 2010 - 2012	Run 2 2015 - 2018	Run 3 2021 - 2023	Run 4 2026 - 2029	Run 5 2031 -
$3\,fb^{-1}$	$9\,fb^{-1}$	$23\,fb^{-1}$	$50\,fb^{-1}$	$300\,fb^{-1}$

↑ Upgrade I (before Run 3) ↑ Upgrade II (before Run 5)

Upgrade I:
CERN-LHCC-2012-007
Upgrade II:
CERN-LHCC-2017-003

Continued improvement reliant on:

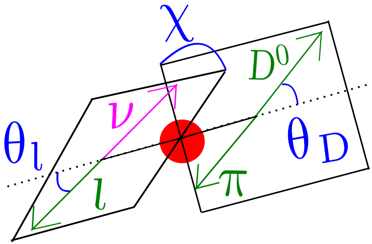
- Simulation size
- Theory collaboration
- Experimental input

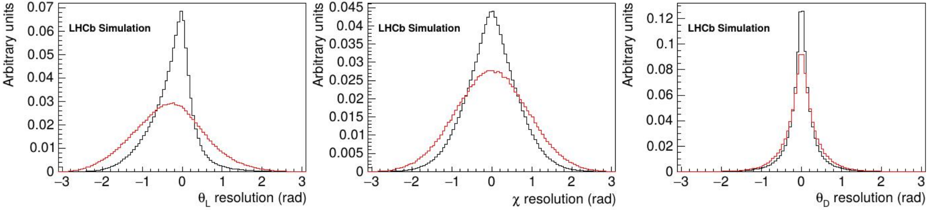


Angular analyses?

If the tension persists we can learn more about new physics with angular and kinematic variables.

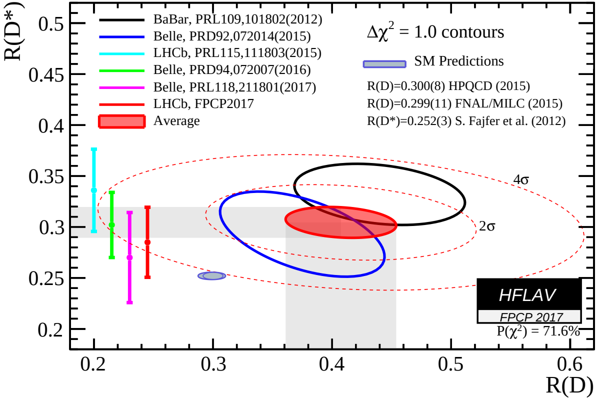
- BaBar has compared q^2 with theory: PRD 88, 072012 (2013)
- Belle has measured τ polarisation: PRL 118, 211801 (2017)
- Unfolding needs careful consideration at LHCb.





Approximate $\gamma_z^B \beta_z^B \approx \gamma_z^{vis} \beta_z^{vis}$ - $B \to D^* \mu\nu$, $B \to D^* \tau\nu$, $\tau \to \mu\nu\nu$

Conclusions



Much work done:

- LHCb has collected a lot of high quality data.
- Measurements are consistent with the experimental average.

Much work to be done:

- Many (unique) measurements still to make.
- These are exciting times.

BACKUP

Hadronic $R(D^*)$ - kinematics

Two-fold ambiguity in determing τ momentum:

$$|p_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)\,|p_{3\pi}|\cos\theta_{\tau,3\pi} \pm E_{3\pi}\sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2\,|p_{3\pi}|^2\sin^2\theta_{\tau,3\pi}}}{2(E_{3\pi}^2 - |p_{3\pi}|^2\cos^2\theta_{\tau,3\pi})}$$

where $\theta_{\tau,3\pi}$ is the angle between the 3π system 3-momentum and the τ flight. Take maximum allowed angle:

$$\theta_{\tau,3\pi}^{max} = \arcsin\left(\frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau\,|p_{3\pi}|}\right)$$

Same for B momentum where Y represents the $D^{*-}\tau^+$ system:

$$|p_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)\,|p_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2\,|p_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |p_Y|^2\cos^2\theta_{B^0,Y})}$$

with:

$$\theta_{B^0,Y}^{max} = \arcsin\left(\frac{m_{B^0}^2 - m_Y^2}{2m_{B^0}\,|p_Y|}\right)$$

Muonic $R(D^*)$ - uncertainties

PRL 115, 111803 (2015)

Table 1: Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	**Absolute size** $(\times 10^{-2})$
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**