Lepton Flavour Universality Violation in $\Lambda_b \to \Lambda_c^* \tau \overline{\nu}_\tau$ decay

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in collaboration with
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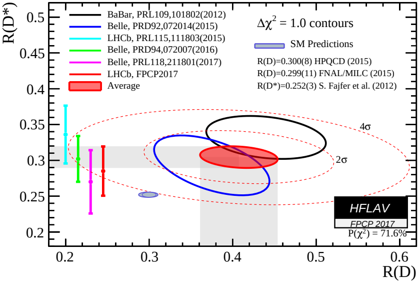
Motivation

- Anomalies at $\sim 4\sigma$ in the universality ratios $R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\overline{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\overline{\nu}_\mu)}$
- At the partonic level, those observable are driven by the transition $b \to c\tau\overline{\nu}_\tau$



Which other channel can be explored?

- Baryonic channels $\Rightarrow \Lambda_b$ decays
  - Test of HQET in the baryonic sector
  - excited state of the Λ_c

$$R(\Lambda_c^*) = \frac{\mathcal{B}(\Lambda_b \to \Lambda_c^* \tau\overline{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c^* \mu\overline{\nu}_\mu)}$$

Charmed Baryon Spectroscopy

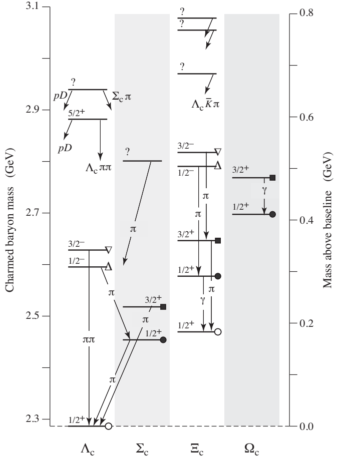
We focus on the Λ_c baryons

Above the ground state, the first excited state is a Λ_c^* isospin doublet:

- $\Lambda_c(2625)$ is a $J^P = 3/2^-$
- $\Lambda_c(2595)$ is a $J^P = 1/2^-$

Properties:

- richly produced at LHCb
- narrow state
- $\Lambda_c^*(2625)$ decays non resonantly to $\Lambda_c \pi\pi$ $(\mathcal{B}(\Lambda_c(2625)^+ \to \Lambda_c^+ \pi\pi) \sim 67\%)$



Form Factor Decomposition

- The form factors arise from a Lorentz decomposition of the hadronic matrix elements
- For the weak vector current we achieve

$$\langle \Lambda_c^*(2625)|\bar{c}\gamma_\mu b|\Lambda_b\rangle = \sum_i F_i(q^2)\bar{u}^\alpha_{c,3/2}(k,\eta(k))S^{(i)}_{\mu\alpha}u_b(p)$$

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where the sets $f_i(q^2)$ and $F_i(q^2)$ count respectively 3 and 4 form factors

- similarly we define the form factors for the weak axial vector current
- helicity decomposition of form factor [Feldmann/Yip 1111.1844]

$$\epsilon^*_\mu(\lambda; q)\langle \Lambda_c^*(2625)|\bar{c}\gamma_\mu b|\Lambda_b\rangle \propto F_\lambda(q^2)$$

- form factor do not vanish at $q^2 = q^2_{\text{max}} = (m_{\Lambda_b} - m_{\Lambda_c^*})^2$

HQE expansion for $\Lambda_b \to \Lambda_c^*$

In the Heavy Quark expansion ($m_b \to +\inf$, $m_c \to +\inf$ but m_c/m_b finite) at leading order

- the form factors are all proportional to one **single** Isgur Wise function $\zeta^\alpha = (v - v')^\alpha \zeta$ [Falk Nucl.Phys. B378 (1992) 79-94]

Beyond the leading order

- two sources of further function at $1/m$ order [Phys.Rept. 245 (1994) 259-396]
  - from local operator arising in the matching of QCD current into HQET: **5 functions**

    $$\zeta_{1b,2b,3b} \qquad \zeta_{1c,2c}$$

  - from non-local operator arising from using the heavy quark limit wave function: **1 function**

    $$\chi$$

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Beyond the leading order

- reduce the degrees of freedom
  - equation of motion relate all except **one** local correction to the leading Isgur Wise function
$$\zeta_{3b} \equiv \zeta_{SL} \qquad \zeta_{1b,2b,1c,2c} \propto \zeta$$
  - from non-local correction can be **reabsorbed** into the leading-power Isgur Wise function
$$\zeta + \chi \frac{m_b + m_c}{2 m_b m_c} \to \zeta$$

Parametrisation of the IW functions

- No first principle in HQET to obtain the functional form of IW functions for the excited states
- We need to infer a parametric dependence of the leading and subleading IW functions:
  - **Exponential Model** [Jenkins, Manohar, Wise, Nucl.Phys. B396 (1993) 38-52]

$$\zeta(q^2)\Big|_{\text{exp}} \equiv \zeta(q^2_{\text{max}}) \exp\left[\rho\left(\frac{q^2}{q^2_{\text{max}}} - 1\right)\right],$$

$$\zeta_{\text{SL}}(q^2)\Big|_{\text{exp}} \equiv \zeta(q^2_{\text{max}})\delta_{\text{SL}} \exp\left[\frac{\rho_{\text{SL}}}{\delta_{\text{SL}}}\left(\frac{q^2}{q^2_{\text{max}}} - 1\right)\right].$$

  - **Linear Parametrisation**: expansion up to the first order in q^2 of the exponential model around the point $q^2 = q^2_{\text{max}}$

Zero recoil sum rule

[Mannel, van Dyk, Phys.Lett. B751 (2015) 48-53]

- **Inclusive** calculation of $\Lambda_b \to \Lambda_b$ **forward matrix element**
- It allows to put **upper bounds** on the parameters of **exclusive matrix element**
- It applies only at the zero recoil point ($q^2 = q^2_{\max}$)
- At $q^2 = q^2_{\max}$ the exponential and nominal parametrisation **coincide** $\to$ the results apply in both case

Assumptions

- the Σ_c states are **isospin suppressed**: only the Λ_c^* contributes beyond the ground state [1709.01920]
- we use the numerical results from $\Lambda_b \to \Lambda_c$ form factors and re-weighted results from $B \to D^{(*)}$ zero recoil sum rule

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Our procedure is not rigorous, however it allows to define a **benchmark point** to extract prediction for the $\Lambda_b \to \Lambda_c^*$ transitions

Observables

For each of the $J = 1/2^-, 3/2^-$ we have

- 2-dim normalised distribution in in q^2 and $\cos\theta_\ell$

$$\frac{1}{\Gamma_0}\frac{\mathrm{d}^2\Gamma^J}{\mathrm{d}q^2\,\mathrm{d}\cos\theta_\ell} = \left(a_\ell^{(J)} + b_\ell^{(J)}\cos\theta_\ell + c_\ell^{(J)}\cos^2\theta_\ell\right)$$

- 1-dim normalised distribution in q^2

$$\frac{1}{\Gamma_0}\frac{\mathrm{d}\Gamma_J}{\mathrm{d}q^2} = 2\left(a_\ell^{(J)} + \frac{c_\ell^{(J)}}{3}\right)$$

where

- θ_ℓ helicity angle of the charged lepton with the Λ_b in the dilepton rest frame
- a_ℓ, b_ℓ, c_ℓ depend on the form factors and kinematics
- $b_\ell \propto A_{FB}$

Numerical analysis

Program:

- Use the benchmark point (and variations) to generate toys (according to arxiv:1709.01920) according to the distribution calculated
- Fit the parameters of the IW functions and extract the sensitivity to them
- Sensitivity study on $R(\Lambda_c^*)$ as a function of luminosity

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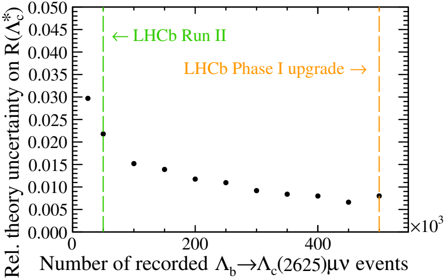
PRELIMINARY!!



Statistical sensitivity on $R(\Lambda_c^*)$ around few %

Conclusion and Outlook

What we've done so far...

- **Parametrisation** of the hadronic form factors for the $\Lambda_b \to \Lambda_c^*$ transition
- Using HQET we relate the form factors to only 2 **independent** Isgur-Wise functions
- The zero recoil sum rule provides a **benchmark point** for the parameters of the leading and subleading Isgur-Wise functions
- A first numerical study shows that LHCb can achieves a **sensitivity of a few % on** $R(\Lambda_c^*)$

...what still needs to be done

- Repeat the 1dim fit with **different benchmark** points
- perform a 2dim fit **adding** the informations from A_{FB}

Appendix

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    $$\zeta_+ \qquad \zeta_-$$

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HQET limit

Vector current in HQE

$$J_V^\mu = C_1(\overline{w})\gamma^\mu + C_2(\overline{w})v^\mu + C_3(\overline{w})v'^\mu + \Delta J_V^\mu\big|_{\mathcal{O}_1} + \Delta J_V^\mu\big|_{\mathcal{O}_8} + \mathcal{O}(\alpha_s/m)\,.$$

Definition of $\overline{w}$: velocity transfer seen from the light degrees of freedom

$$\overline{w} \equiv w\left(1 + \frac{\overline{\Lambda}}{m_b} + \frac{\overline{\Lambda}'}{m_c}\right) - \left(\frac{\overline{\Lambda}}{m_c} + \frac{\overline{\Lambda}'}{m_b}\right)\,.$$

Correction to vector current

$$\Delta J_{V\mu}\big|_{\mathcal{O}_{1(8)}} = \sqrt{4}\,\overline{u}_\alpha(M_{\Lambda_c^*}v', \eta, s_c)(\mathcal{O}_{1(8)})_{\mu\beta}\,u(M_{\Lambda_b}v, s_b)\zeta^{\alpha\beta}_{(b)(c)}(w)\,,$$

$$\zeta^{\alpha\beta}_{(q)}(w) = (v - v')^\alpha\left[\zeta_1^{(q)}(w)v^\beta + \zeta_2^{(q)}(w)v'^\beta\right] + g^{\alpha\beta}\zeta_3^{(q)}(w)\,.$$

$$(\mathcal{O}_1)_{\mu\beta} = \gamma_\mu\gamma_\beta \qquad (\mathcal{O}_8)_{\mu\beta} = \gamma_\beta\gamma_\mu$$

Non local correction to $\zeta(q^2)$

In the case of heavy to light transition, the lagrangian which describes the correction to the heavy quark wave function is:

$$\frac{1}{m_Q}\mathcal{L}_1 = \frac{1}{2m_Q}\overline{h}_v(iD)^2 h_v + C_{magn}(\mu)\frac{g}{4m_Q}\overline{h}_v\sigma_{\alpha\beta}G^{\alpha\beta}h_v$$

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The insertion of $\mathcal{L}_1$ in the heavy quark line is evaluated by:

$$\langle\Lambda'(v')|i\int \mathrm{d}x\ \mathcal{T}\left\{J_i(0),\mathcal{L}_1(x)\right\}|\Lambda(v)\rangle = 2\ \overline{\Lambda}\chi(w)\overline{u}(v')\Gamma_i u(v)$$

Due to the **spin** structure of baryons, the chromomagnetic operator in $\mathcal{L}_1$ **doesn't** play any role

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What changes if I have a **heavy to heavy** transition? The time-ordered product will contain a term for the b **quark** and one for the c **quark**

Observables

Forward-Backward asymmetry

$$A_{\mathrm{FB}}(q^2) \equiv \frac{\omega_{A_{\mathbf{FB}}}(q^2)}{\mathrm{d}\Gamma^J/\mathrm{d}q^2} = \frac{b_\ell^{(J)}(q^2)}{2\left(a_\ell^{(J)}(q^2) + \frac{c_\ell^{(J)}(q^2)}{3}\right)}$$

Flat Term

$$F_{\mathrm{H}}(q^2) \equiv \frac{\omega_{F_{\mathbf{H}}}(q^2)}{\mathrm{d}\Gamma^J/\mathrm{d}q^2} = \frac{\left[a_\ell^{(J)}(q^2) + c_\ell^{(J)}(q^2)\right]}{\left[a_\ell^{(J)}(q^2) + \frac{1}{3}c_\ell^{(J)}(q^2)\right]}$$

Coefficients of the $J^P = 3/2^-$ state

$$
\begin{aligned}
a_\ell^{(3/2)} =& \Bigg[|F_{1/2,t}|^2 \frac{m_\ell^2}{q^2} (M_{\Lambda_b} - M_{\Lambda_c^*})^2 + \Bigg(|F_{1/2,0}|^2 (M_{\Lambda_b} + M_{\Lambda_c^*})^2 \\
&+ (|F_{1/2,\perp}|^2 + 3|F_{3/2,\perp}|^2)(m_\ell^2 + q^2) \Bigg) + |G_{1/2,t}|^2 \frac{m_\ell^2}{q^2} (M_{\Lambda_b} + M_{\Lambda_c^*})^2 \\
&+ \Bigg(|G_{1/2,0}|^2 (M_{\Lambda_b} - M_{\Lambda_c^*})^2 + (|G_{1/2,\perp}|^2 + 3|G_{3/2,\perp}|^2)(m_\ell^2 + q^2) \Bigg) \Bigg] , \\
b_\ell^{(3/2)} =& \; 2 \left[(F_{1/2,t} F_{1/2,0}) + (G_{1/2,t} G_{1/2,0}) \right] \frac{m_\ell^2}{q^2} (M_{\Lambda_b}^2 - M_{\Lambda_c^*}^2) \\
&- 4\, q^2 \left[F_{1/2,\perp} G_{1/2,\perp} + 3 F_{3/2,\perp} G_{3/2,\perp} \right] , \\
c_\ell^{(3/2)} =& - \left(1 - \frac{m_\ell^2}{q^2} \right) \Bigg[|F_{1/2,0}|^2 (M_{\Lambda_b} + M_{\Lambda_c^*})^2 - q^2 (|F_{1/2,\perp}|^2 + 3|F_{3/2,\perp}|^2) \\
&+ |G_{1/2,0}|^2 (M_{\Lambda_b} - M_{\Lambda_c^*})^2 - q^2 (|G_{1/2,\perp}|^2 + 3|G_{3/2,\perp}|^2) \Bigg] .
\end{aligned}
$$

Zero Recoil Sum Rule - Technicalities 1

[Mannel, van Dyk, Phys.Lett. B751 (2015) 48-53]

$$T_\Gamma(\epsilon) = \frac{1}{N_\Gamma} \int \mathrm{d}^4x \; e^{i(v\cdot x)\epsilon} \langle \Lambda_b(P) | \mathcal{T}\left\{ \bar{b}_v(x) \Gamma c_v(x) \bar{c}_v(0) \Gamma b_v(0) \right\} | \Lambda_b(P) \rangle$$

$$I_{n,\Gamma}(\epsilon_M) \equiv -\frac{1}{2\pi i} \oint\limits_{|\epsilon|=\epsilon_M} \epsilon^n T_\Gamma(\epsilon) \mathrm{d}\epsilon$$

In the case of axial vector current $\Gamma = \gamma_\mu \gamma_5$

$$I_{0,A}(\epsilon_M) = \frac{1}{N_A} \sum_{X_c, \epsilon \leq \epsilon_M} \langle \Lambda_b(v,s) | \bar{b}_v \gamma_\mu \gamma_5 c_v | X_c(v) \rangle \langle X_c(v) | \bar{c}_v \gamma^\mu \gamma_5 b_v | \Lambda_b(v,s) \rangle \equiv G + G_{inel}$$

- G is the elastic contribution and comes from the X_c ground state
- G_{inel} encodes the excited states contribution

Zero Recoil Sum Rule - Technicalities 2

[Mannel, van Dyk, Phys.Lett. B751 (2015) 48-53]

OPE for $I_{0,A}(\epsilon_M)$

$$I_{0,A}(\epsilon_M) = \xi_A^{\text{pert}}(\epsilon_M,\mu) - \Delta^A_{1/m^2}(\epsilon_M,\mu) - \Delta^A_{1/m^3}(\epsilon_M,\mu) + \mathcal{O}(\Lambda^4_{\text{had}}/m_b^4, \Lambda^4_{\text{had}}/m_c^4),$$

where $\xi_A^{\text{pert}}(\epsilon_M,\mu)$, $\Delta^A_{1/m^2}(\epsilon_M,\mu)$ and $\Delta^A_{1/m^3}(\epsilon_M,\mu)$ are calculable/estimated

If now we use the $\Lambda_b \to \Lambda_c$ lattice form factors and the values extracted for $\xi_A^{\text{pert}}(\epsilon_M,\mu)$, $\Delta^A_{1/m^2}(\epsilon_M,\mu)$ and

The lattice form factor for $\Lambda_b \to \Lambda_c$ transition saturate the sum rule

The Δ_{1/m^4} and Δ_{1/m^5} contributions can be sizeable. However not present in the literature for the baryon case.

We re-weighted the contribution from $B \to D^{(*)}$ sum rule, by the ratio of the $\Delta_{1/m^4} + \Delta_{1/m^5}$ with respect to $\Delta_{1/m^2} + \Delta_{1/m^3}$ in the baryonic case.