Probing New Physics in $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\ell\bar{\nu}$

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Lepton Flavor Universality

- LFU in the SM: $\mathcal{L}_{\text{Yukawa}} = -\bar{q}_L \mathcal{Y}_u u_R \widetilde{\phi} - \bar{q}_L \mathcal{Y}_d d_R \phi - \bar{L}_L \mathcal{Y}_\ell \ell_R \phi + \text{h.c.}$
  $\rightarrow$ After SSB: lepton mass and (negligible) Higgs interaction.
- τ reconstruction difficult due to hadronic resonances ~ 1 GeV.
- Experimental measurements hint at violation of LFU.

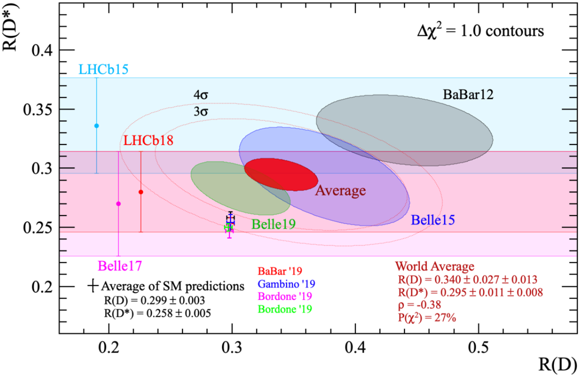
Semileptonic decay:

$\bar{B} \rightarrow D^{(*)} \ell \bar{\nu}$

[Rotondo, priv. com.]

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \bar{\nu})}{\mathcal{B}(B \rightarrow D^{(*)} \ell \bar{\nu})}$$

$\sim 3.9\sigma$



- Model-independent analysis of New Physics is desirable.
- We consider the electroweak Hamiltonian at the scale $\mu \sim m_b$

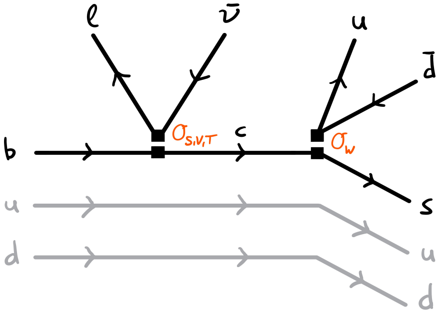
$$\mathcal{H}_{\text{eff}} = \frac{4\widetilde{G}_F \widetilde{V}_{cb}}{\sqrt{2}} \sum_i \mathcal{C}_i \mathcal{O}_i \ .$$

- Most general set of operators for $b \to c\ell\bar{\nu}_L$ up to dim-6 is

$$\begin{aligned} \mathcal{O}_{S,L} &= [\bar{c}P_L b][\bar{\ell}P_L\nu_\ell] \ , & \mathcal{O}_{S,R} &= [\bar{c}P_R b][\bar{\ell}P_L\nu_\ell] \\ \mathcal{O}_{V,L(R)} &= [\bar{c}\gamma^\mu P_{L(R)} b][\bar{\ell}\gamma_\mu P_L\nu_\ell] \ , & \mathcal{O}_{V,R} &= [\bar{c}\gamma^\mu P_R b][\bar{\ell}\gamma_\mu P_L\nu_\ell] \\ \mathcal{O}_T &= [\bar{c}\sigma^{\mu\nu} b][\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell] \ . \end{aligned}$$

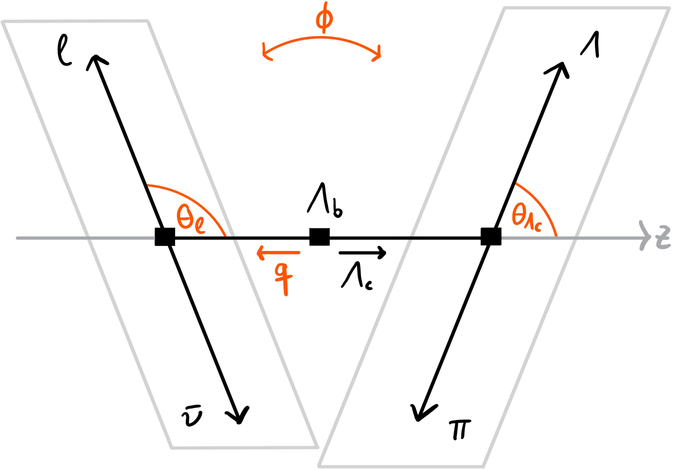
- Motivation: SMEFT is able to generate all operators above.
  [Catà, Jung, 1505.05804].

$$\Lambda_b^0 \to \Lambda_c^+(\to \Lambda^0 \pi^+)\ell^- \bar{\nu}_\ell$$



- Λ_b assumed to be unpolarized.
- Narrow width approximation of Λ_c since $c\tau_{\Lambda_c} \approx 60\mu m$.

Kinematic Variables



$$m_\ell^2 \le q^2 \le (m_{\Lambda_b} - m_{\Lambda_c})^2 \,, \quad \cos\theta_\ell,\ \theta_{\Lambda_c} \in [-1,1] \,, \quad \phi \in [0, 2\pi]$$

Decay Width

Angular Distribution

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_\ell\mathrm{d}\cos\theta_{\Lambda_c}\mathrm{d}\phi} \equiv \frac{3}{8\pi}\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}K(q^2,\cos\theta_\ell,\cos\theta_{\Lambda_c},\phi)$$

$$\begin{aligned} K = &\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right) \\ &+ \left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\cos\theta_{\Lambda_c} \\ &+ \left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\sin\theta_{\Lambda_c}\sin\phi \\ &+ \left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)\sin\theta_{\Lambda_c}\cos\phi \end{aligned}$$

- 10 angular coefficients (observables).
- Number of K_i's fixed by angular momentum conservation.

Results can be cast into compact expressions, e.g.

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} K_{2ss} = \frac{\alpha}{2}\,\mathrm{Re}\left\{\left(1+\frac{m_\ell^2}{q^2}\right)A_{\perp_1}A_{\|_1}^* + 2A_{\perp_0}A_{\|_0}^* + 2\frac{m_\ell^2}{q^2}A_{\perp_t}A_{\|_t}^*\right\}$$

$$-\,2\,\alpha\frac{m_\ell}{\sqrt{q^2}}\,\mathrm{Re}\left\{A_{\perp_0}^T A_{\|_0}^* + A_{\perp_1}^T A_{\|_1}^* + (\perp \leftrightarrow \|)\right\}$$

$$+2\,\alpha\,\mathrm{Re}\left\{\left(1+\frac{m_\ell^2}{q^2}\right)A_{\perp_1}^T A_{\|_1}^{T*} + 2\frac{m_\ell^2}{q^2}A_{\perp_0}^T A_{\|_0}^{T*}\right\}.$$

- Transversity amplitdues:

$$A_{\perp_t} \equiv \sqrt{2}\mathcal{N}\sqrt{s_+}\frac{m_{\Lambda_b}-m_{\Lambda_c}}{m_\ell}\, f_t^V(q^2)\left[\frac{m_\ell}{\sqrt{q^2}}\,\mathcal{C}_{V,+} + \frac{\sqrt{q^2}}{m_b-m_c}\,\mathcal{C}_{S,+}\right].$$

- In total 10, all of factorized form

$$A_{\perp_i/\|_i} \sim f * \mathcal{C}\,.$$

Non-perturbative Input

1. $\Lambda_b \to \Lambda_c$ form factors $(3+3+4=10)$,

$$\langle \Lambda_c | \bar{c}\gamma^\mu b | \Lambda_b \rangle \equiv \bar{u}_{\Lambda_c} \Bigg[f_t^V(q^2)(m_{\Lambda_b} - m_{\Lambda_c}) \frac{q^\mu}{q^2} + f_0^V(q^2) \frac{m_{\Lambda_b} + m_{\Lambda_c}}{s_+} \left(p^\mu + k^\mu - \frac{q^\mu}{q^2}(m_{\Lambda_b}^2 - m_{\Lambda_c}^2) \right) + f_\perp^V(q^2) \left(\gamma^\mu - \frac{2m_{\Lambda_c}}{s_+} p^\mu - \frac{2m_{\Lambda_b}}{s_+} k^\mu \right) \Bigg] u_{\Lambda_b} \, .$$

Lattice data available: [Detmold, Lehner, Meinel, 1503.01421].

2. $\Lambda_c \to \Lambda\pi$ angular asymmetry parameter from [PDG, BESIII]:

$$\frac{d\Gamma^{\Lambda_c \to \Lambda\pi}}{d\cos\Theta_{\Lambda_c}} \sim 1 + \alpha \cos\Theta_{\Lambda_c} \, , \quad \alpha = -0.82 \pm 0.09 \, .$$

What would be the benefit of measuring this decay?

- Measurement of all angular observables by LHCb is possible: [LHCb, 1709.01920]

$$
\begin{aligned}
&N(\Lambda_b^0 \to \Lambda_c^+(\to \Lambda^0\pi^+)\mu^-\bar{\nu}) \\
&\simeq N(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\bar{\nu}) \times \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda^0\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} \\
&\simeq 0.5 \cdot 10^6 \simeq 10 \times N(\Lambda_b \to \Lambda_c^*(2625)\mu\bar{\nu}_\mu)\ .
\end{aligned}
$$

[Böer, Bordone, Graverini, Owen, Rotondo, van Dyk, 1801.08367].

- 25 real parameters from non-redundant combinations of the $\mathcal{C}_i$'s.

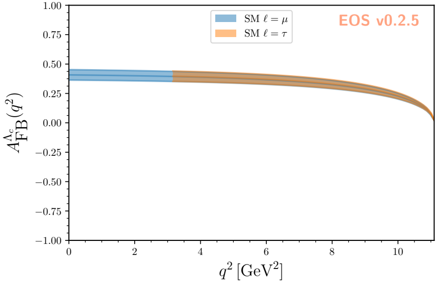
  → For $m_\ell = 0$, angular observables are sensitive to 12 out of 25, for $m_\ell \neq 0$ to 22 out of 25 combinations. High sensitivity!

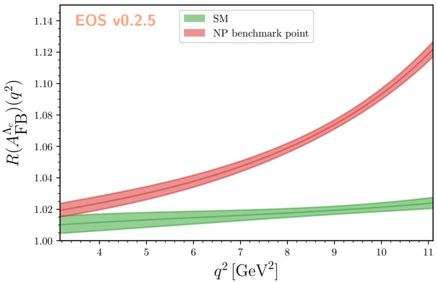
  → $\bar{B} \to D^{(*)}\tau\bar{\nu}$ distribution not sensitive to $\mathcal{C}_{V,-}$ and $\mathcal{C}_{S,-(+)}$, $\mathcal{C}_{i,\pm} = \mathcal{C}_{i,L} \pm \mathcal{C}_{i,R}$.

Hadronic Forward-Backward Asymmetry

$$A_{\mathrm{FB}}^{\Lambda_c} = K_{2ss} + \frac{1}{2} K_{2cc}$$

$$R(A_{\mathrm{FB}}^{\Lambda_c}) \equiv \frac{\left[A_{\mathrm{FB}}^{\Lambda_c}\right]_{\ell=\tau}}{\left[A_{\mathrm{FB}}^{\Lambda_c}\right]_{\ell=\mu}}$$





- New Physics benchmark point [Murgui et. al., 1904.09311]:

$$\mathcal{C}_{V,L}^{(\tau)} = 1.15\,, \quad \mathcal{C}_{V,R}^{(\tau)} = 0\,, \quad \mathcal{C}_{S,L}^{(\tau)} = -0.3\,, \quad \mathcal{C}_{S,R}^{(\tau)} = +0.3\,, \quad \mathcal{C}_{T}^{(\tau)} = 0\,.$$

- $\delta_R \sim 1\%$, compared to $\delta_{\mathcal{R}(D)} \sim 2\%$.

Summary

- Complete four-fold distribution of $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\ell\bar{\nu}$
  $\to$ For the first time with $m_\ell \neq 0$ in presence of all weak effective operators.

- High sensitivity to BSM parameters in the cascade decay.
  $\to$ Accessible set of combinations from Wilson coefficients large, 22 out of 25 combinations for $m_\ell \neq 0$.

- Hadronic forward-backward asymmetry
  $\to$ Attractive observable for LHCb for a first measurement.
  $\to$ Small theory uncertainty.

Thanks for your attention!

Angular Observables

	SM		BMP #1	BMP #2	BMP #3
obs.	$\ell = \mu$	$\ell = \tau$	$\ell = \tau$	$\ell = \tau$	$\ell = \tau$
K_{1cc}	$+0.206 \pm 0.004$	$+0.310 \pm 0.001$	$+0.311 \pm 0.000$	$+0.307 \pm 0.001$	$+0.343 \pm 0.001$
K_{1c}	-0.134 ± 0.004	$+0.016 \pm 0.003$	$+0.037 \pm 0.002$	-0.073 ± 0.002	$+0.080 \pm 0.003$
K_{2ss}	$+0.288 \pm 0.032$	$+0.221 \pm 0.024$	$+0.228 \pm 0.025$	$+0.167 \pm 0.018$	$+0.252 \pm 0.027$
K_{2cc}	$+0.115 \pm 0.013$	$+0.183 \pm 0.020$	$+0.193 \pm 0.021$	$+0.122 \pm 0.013$	$+0.130 \pm 0.013$
K_{2c}	-0.164 ± 0.018	-0.031 ± 0.004	-0.017 ± 0.003	-0.123 ± 0.013	-0.080 ± 0.009
K_{4sc}	$+0.063 \pm 0.008$	$+0.023 \pm 0.003$	$+0.022 \pm 0.002$	$+0.026 \pm 0.003$	$+0.001 \pm 0.000$
K_{4s}	$+0.125 \pm 0.015$	$+0.063 \pm 0.007$	$+0.065 \pm 0.007$	$+0.161 \pm 0.017$	$+0.039 \pm 0.004$

Set of Combinations

$$
\begin{aligned}
\sigma^{\pm}_{V,1} &= \frac{1}{2}|\mathcal{C}_{V,\pm}|^2\,, & \sigma_{V,2} &= -\mathcal{C}_{V,-}\mathcal{C}^*_{V,+}\,, & \sigma_{T,1} &= \frac{1}{2}|\mathcal{C}_T|^2\,,\\
\sigma^{\pm}_{S,1} &= \frac{1}{2}|\mathcal{C}_{S,\pm}|^2\,, & \sigma_{S,2} &= -\mathcal{C}_{S,-}\mathcal{C}^*_{S,+}\,, & \sigma^{\pm}_{VT,1} &= \frac{1}{2}\mathcal{C}_{V,\pm}\mathcal{C}^*_T\,,\\
\sigma^{\pm}_{VS,1} &= \frac{1}{2}\mathcal{C}_{V,\pm}\mathcal{C}^*_{S,\pm} & \sigma_{VS,2} &= -\mathcal{C}_{V,-}\mathcal{C}^*_{S,+}\,, & \sigma^{\pm}_{ST,1} &= \frac{1}{2}\mathcal{C}_{S,\pm}\mathcal{C}^*_T\,.\\
& & \sigma_{SV,2} &= -\mathcal{C}_{S,-}\mathcal{C}^*_{V,+}\,, & &
\end{aligned}
$$

$$
\Sigma(m_\ell = 0) \equiv \{\sigma^{\pm}_{V,1}, \sigma^{\pm}_{S,1}, \sigma_{T,1}, \mathrm{Re}\,\sigma_{V,2}, \mathrm{Im}\,\sigma_{V,2}, \mathrm{Re}\,\sigma_{S,2}, \mathrm{Re}\,\sigma^{\pm}_{ST,1}, \mathrm{Im}\,\sigma^{\pm}_{ST,1}\}
$$

$$
\Sigma \equiv \Sigma(m_\ell = 0) \;\cup\; \{\mathrm{Re}\,\sigma^{\pm}_{VS,1}, \mathrm{Im}\,\sigma^{\pm}_{VS,1}, \mathrm{Re}\,\sigma_{VS,2}, \mathrm{Re}\,\sigma_{SV,2}, \mathrm{Re}\,\sigma^{\pm}_{VT,1}, \mathrm{Im}\,\sigma^{\pm}_{VT,1}\}
$$

References

We crosschecked our results with

- [Datta, Kamali, Meinel, Rashed, 1702.02243],
- [Shivashankara, Wu, Datta, 1502.07230]*,
- [Gutsche, Ivanov, Körner, Lyubovitskij, 1502.04864].