BSM Constraints for $\Lambda_b \to \Lambda\tau^+\tau^-$

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Outline for today:

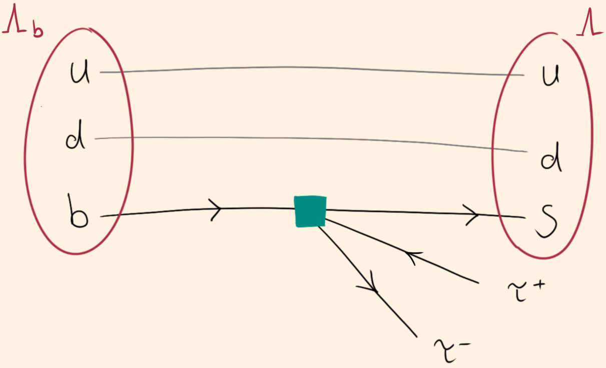
SM Prediction

- LEFT
- $\bar{c}c$ Resonances

BSM Constraints

- $U(2)^5$ Flavour Symmetry
- Possible Enhancement of $\Lambda_b \to \Lambda\tau^+\tau^-$

$\Lambda_b \to \Lambda\tau^+\tau^-$



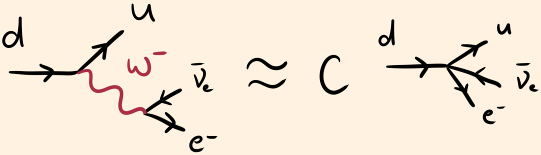
$b \to s\bar{\ell}\ell$

$\Rightarrow$ low energy EFT (LEFT)

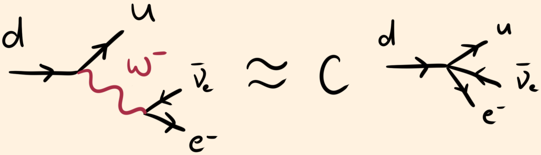
Hadronic Structure

$\Rightarrow$ lattice QCD

LEFT



LEFT



Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_{\text{em}}}{4\pi} \sum_i C_i(\mu)\mathcal{O}_i(\mu),$$

relevant operators for $b \to s\bar{\ell}\ell$:

$$\mathcal{O}_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu},$$
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma^5 \ell)$$

Hadronic Structure of the Baryons

The internal structure of Λ_b and Λ is determined by low energy QCD.
$\Rightarrow$ transition described by lattice QCD Form Factors

William Detmold and Stefan Meinel. *$\Lambda_b \to \Lambda \ell^+ \ell^-$ form factors, differential branching fraction, and angular observables from lattice QCD with relativistic b quarks.* arXiv:1602.01399 [hep-lat]. Apr. 2016

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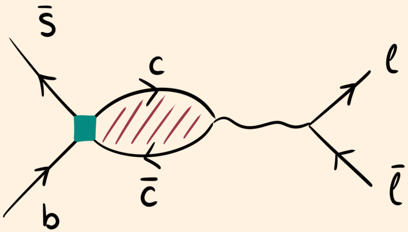
$$\langle \Lambda(k)\,|\bar{s}\,\gamma^\mu\, b|\Lambda_b(p)\rangle = +\bar{u}_\Lambda(k)\Big[f_0(q^2)\,(m_{\Lambda_b}-m_\Lambda)\frac{q^\mu}{q^2}$$
$$+f_+(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{s_+}\left(p^\mu+k^\mu-(m_{\Lambda_b}^2-m_\Lambda^2)\frac{q^\mu}{q^2}\right)$$
$$+f_\perp(q^2)\left(\gamma^\mu-\frac{2m_\Lambda}{s_+}p^\mu-\frac{2m_{\Lambda_b}}{s_+}k^\mu\right)\Big]u_{\Lambda_b}(p)$$

William Detmold and Stefan Meinel. $\Lambda_b \to \Lambda\ell^+\ell^-$ *form factors, differential branching fraction, and angular observables from lattice QCD with relativistic b quarks.* arXiv:1602.01399 [hep-lat]. Apr. 2016

Charm (Resonance) Contributions



4-Fermion interactions

$$\mathcal{O}_1 = (\bar{s}_L^{\alpha}\gamma_\mu c_L^{\beta})(\bar{c}_L^{\beta}\gamma^\mu b_L^{\alpha})$$
$$\mathcal{O}_2 = (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu b_L)$$

$c\bar{c}$ Resonances: $J/\psi, \psi(2S)$

Narrow width approximation:

$$A_R^{\text{res}}(q^2) = \frac{m_R\Gamma_R}{m_R^2 - q^2 - im_R\Gamma_R}$$

$\Rightarrow$ can be implemented via a shift to C_9

$$C_9 \to C_9 + Y(C_1, C_2, q^2) + \frac{16\pi^2}{\mathcal{F}(q^2)}\sum_R \eta_R e^{i\delta_R}\frac{q^2}{m_R^2}A_R^{\text{res}}(q^2)$$

Marzia Bordone et al. *Short- vs. long-distance physics in B to $K^{(*)}\ell^+\ell^-$: a data-driven analysis.* arXiv:2401.18007 [hep-ph]. May 2024

Resonance Parameters

$\Rightarrow$ some parameters need to be found from data

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Resonance Strength η_R

assume $\mathcal{B}(\Lambda_b \to \Lambda R \to \Lambda \ell^+ \ell^-)$
$= \mathcal{B}(\Lambda_b \to \Lambda R)\mathcal{B}(R \to \ell^+ \ell^-)$

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Resonance Phases δ_R

use differential branching fraction of e.g. $\Lambda_b \to \Lambda \mu\mu$

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✓

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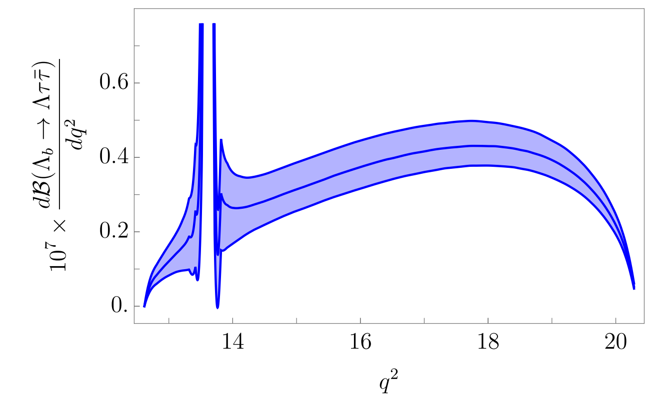
✗

Branching Fraction



$$\int_{15\ \mathrm{GeV}^2}^{(M_{\Lambda_b}-M_\Lambda)^2} \frac{d\mathcal{B}(\Lambda_b \to \Lambda\tau^+\tau^-)}{dq^2}\,dq^2 = 1.950^{+0.31}_{-0.28} \times 10^{-7}$$

Ideal Measurement:

- removes lots of theoretical uncertainties
- avoids normalisation modes such as $\Lambda_b \to J/\psi\Lambda$

$$R_{\Lambda_b}^{\tau/\mu} = \frac{\mathcal{B}(\Lambda_b \to \Lambda\tau\bar{\tau})}{\mathcal{B}(\Lambda_b \to \Lambda\mu\bar{\mu})} = 0.53 \pm 0.03$$

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↑ Please measure this one ↑

- BSM -

Flavour Structure of New Physics

SMEFT: assume new physics particles are heavy compared to SM
$\Rightarrow$ can describe interactions using SM particles only

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda} \mathcal{O}_i^{d=5} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + ...$$

Darius A. Faroughy et al. *Flavour symmetries in the SMEFT*. arXiv:2005.05366 [hep-ph]. Aug. 2020

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No Flavour Structure	$\Leftrightarrow$	Flavour Universal $U(3)^5$
2499 paramters		47 parameters

Middle ground: $U(2)^5$ symmetry

Darius A. Faroughy et al. *Flavour symmetries in the SMEFT.* arXiv:2005.05366 [hep-ph]. Aug. 2020

NP EFT

- quark flavour symmetry:
  $\mathcal{G}_F = U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e = U(2)^5$
  $\Rightarrow q_L^3, \ell_L^3, t_R, b_R, \tau_R$ are singlet states under $\mathcal{G}_F$

- assume NP couples to third generation:

$$\mathcal{L}_{\text{eff}}^{\text{NP}} \supset \sum_k C_k \mathcal{O}_k + \text{ h.c.}$$

$$\mathcal{O}_{\ell q}^{\pm} = (\bar{q}_L^3 \gamma^\mu q_L^3)(\bar{\ell}_L^3 \gamma_\mu \ell_L^3) \pm (\bar{q}_L^3 \gamma^\mu \sigma^a q_L^3)(\bar{\ell}_L^3 \gamma_\mu \sigma^a \ell_L^3)$$
$$\mathcal{O}_S = (\bar{\ell}_L^3 \tau_R)(\bar{b}_R q_L^3)$$

Lukas Allwicher et al. *Probing third-generation New Physics with $K \to \pi\nu\bar{\nu}$ and $B \to K^{(*)}\nu\bar{\nu}$*. arXiv:2410.21444 [hep-ph]. Jan. 2025

$U(2)_q$ breaking

- operators like $\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$ not invariant under $U(2)_q$!

introduce a $U(2)_q$ doublet spurion:

$$\tilde{V} = -\epsilon \begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$$

breaks the flavour symmetry in a SM like way

$\Rightarrow$ Now we can write terms like $(\bar{q}_L^i \tilde{V}_i \gamma_\mu P_L q_L^3)$

NP Contributions to $\Lambda_b \to \Lambda\tau^+\tau^-$

assume NP leads to shifts $C_9 \to C_9 + \Delta_9$ and $C_{10} \to C_{10} + \Delta_{10}$

$$\Delta_9 = -\frac{\epsilon C_{lq}^+ \sqrt{2}\pi}{G_F V_{tb} \alpha_{em}}, \qquad \Delta_{10} = \frac{\epsilon C_{lq}^+ \sqrt{2}\pi}{G_F V_{tb} \alpha_{em}}$$

best fit for $C_{lq}^{\pm}, C_S, \epsilon$ from other observables:

- $\sigma(pp \to \ell\ell)$
- EWPO
- R_D, R_{D^*}
- $\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})$
- $\mathcal{B}(B \to K\nu\bar{\nu})$
- $\mathcal{B}(K \to \pi\nu\bar{\nu})$

⇒ NP contribution to:

$$R_{\Lambda_b}^{\tau/\mu} = \frac{\mathcal{B}(\Lambda_b \to \Lambda\tau\bar{\tau})}{\mathcal{B}(\Lambda_b \to \Lambda\mu\bar{\mu})} \approx 300 \times R_{\Lambda_b}^{\tau/\mu}\big|_{\text{SM}}$$

Conclusion

We have found theory predictions:

$$\int_{15\ \text{GeV}^2}^{(M_{\Lambda_b}-M_\Lambda)^2} \frac{d\mathcal{B}(\Lambda_b \to \Lambda\tau^+\tau^-)}{dq^2}\, dq^2 = 1.950^{+0.31}_{-0.28} \times 10^{-7}$$

$$R^{\tau/\mu}_{\Lambda_b} = \frac{\mathcal{B}(\Lambda_b \to \Lambda\tau\bar{\tau})}{\mathcal{B}(\Lambda_b \to \Lambda\mu\bar{\mu})} = 0.53 \pm 0.03$$

⇒ In the $U(2)^5$ model:

$$R^{\tau/\mu}_{\Lambda_b} \approx 300 \times R^{\tau/\mu}_{\Lambda_b}\Big|_{\text{SM}}$$

-BACKUP SLIDES-

Resonance Parameters

R	m_R [GeV]	Γ_R [GeV]	$\mathcal{B}(\Lambda_b \to R\Lambda)$	$\mathcal{B}(R \to \ell^+\ell^-)$
J/ψ	3.097	$92.6 \cdot 10^{-6}$	$(6.3 \pm 1.3) \cdot 10^{-4}$	$(5.96 \pm 0.00) \cdot 10^{-2}$
$\psi(2S)$	3.686	$293.0 \cdot 10^{-6}$	$(3.2 \pm 0.7) \cdot 10^{-4}$	$(3.1 \pm 0.4) \cdot 10^{-3}$

Table: Masses and decay width of the resonances J/ψ and $\psi(2S)$. For the J/ψ the value refers to the case of $\ell = \mu$ while for $\psi(2S)$ we consider $\ell = \tau$.

Resonance Phases

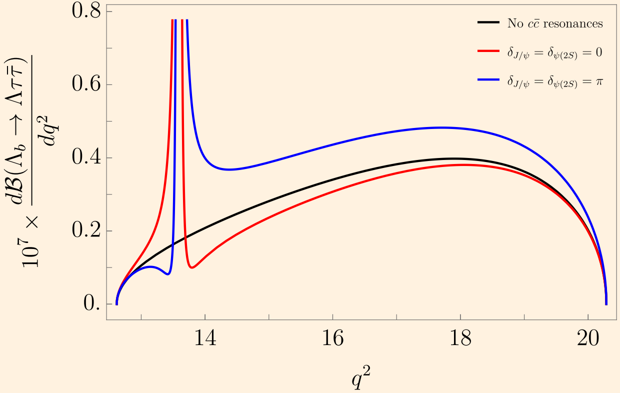

Figure: Dependence of the $d\mathcal{B}/dq^2$ on the phases of the $c\bar{c}$ resonances