New Physics models and constraints from Λ_b and B_c decays

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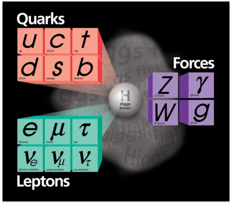
Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

Flavor physics with b-baryons and B_c mesons – MITP, 26 May 2026

Why hunt for New Physics in b decays?



Shortcomings of the Standard Model (SM)

- electroweak hierarchy problem
- flavor problem
- neutrino masses
- dark matter & dark energy
- baryogenesis

New Physics (NP) in the b system

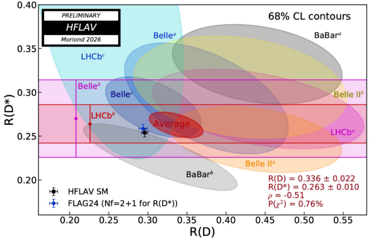
- flavor violation suppressed in the SM
- b is long-lived:
  - ➢ rare b decays not that rare
  - ➢ relevant interference with SM
- plethora of possible channels

Primary routes to discovery

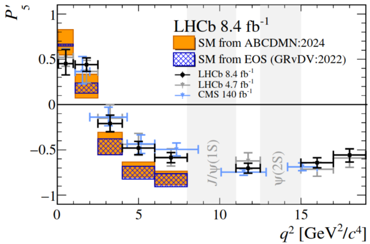
- theoretically clean observables
- flavor changing neutral currents
- light NP in the final state

Hints for New Physics from B meson decays?

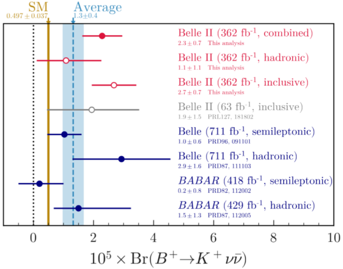
$\mathcal{R}(D^{(*)})$



$b \to s\mu^+\mu^-$



$B \to K\nu\bar{\nu}$

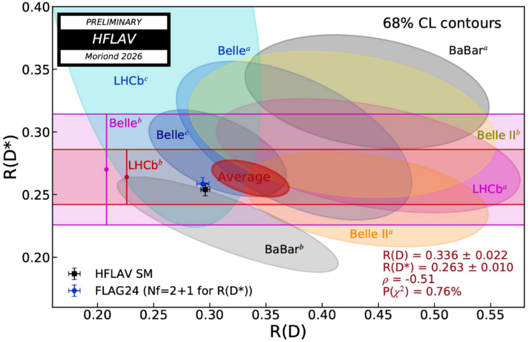


Tension in charged current B decays

Lepton flavor universality in $b \to c$ decays

$$\mathcal{R}(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \qquad \ell = e, \mu$$

- clean test of SM, as form factor uncertainties mostly cancel in ratio
- long-standing tension between SM and data, recently reduced to 2σ level
- first $\mathcal{R}(D^{**})$ measurement with large uncertainties ➢ inconclusive

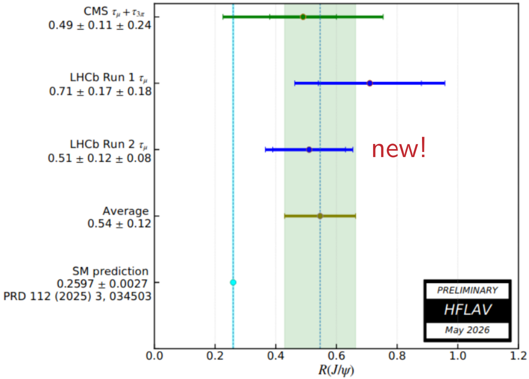


Recent LHCb news from $B_c \to J/\psi\tau\nu$

Lepton flavor universality probe using B_c

$$\mathcal{R}(J/\psi) = \frac{\text{BR}(B_c \to J/\psi\tau\nu)}{\text{BR}(B_c \to J/\psi\ell\nu)} \qquad \ell = e, \mu$$

- SM prediction with 1% accuracy using lattice QCD form factor determination HPQCD (2025)
- recent HFLAV average: $\sim 2\sigma$ enhancement w.r.t. SM



Naive expectation: similar NP effects in $\mathcal{R}(D^*)$ and $\mathcal{R}(J/\psi)$

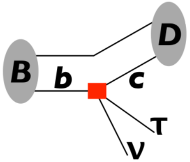
Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently[1] by

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb}\Big[(1+C^{\tau}_{V_L})O^{\tau}_{V_L} + C^{\tau}_{S_R}O^{\tau}_{S_R} + C^{\tau}_{S_L}O^{\tau}_{S_L} + C^{\tau}_{T}O^{\tau}_{T}\Big]$$

with the vector, scalar and tensor operators

$$O^{\tau}_{V_L} = (\bar{c}\gamma^{\mu}P_L b)\,(\bar{\tau}\gamma_{\mu}P_L\nu_{\tau})$$
$$O^{\tau}_{S_R} = (\bar{c}P_R b)\,(\bar{\tau}P_L\nu_{\tau})$$
$$O^{\tau}_{S_L} = (\bar{c}P_L b)\,(\bar{\tau}P_L\nu_{\tau})$$
$$O^{\tau}_{T} = (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_{\tau})$$



Note: $O^{\tau}_{V_R} = (\bar{c}\gamma^{\mu}P_R b)\,(\bar{\tau}\gamma_{\mu}P_L\nu_{\tau})$ not generated at dimension-six level in the $SU(2)_L \times U(1)_Y$-invariant theory

[1] assuming heavy/no ν_R and NP only in τ channel

Possible single-particle explanations

Possible New Physics scenarios (tree level!)

$C_{V_L}^{\tau}$	vector $\mathrm{SU}(2)_L$-triplet W' boson ➢ disfavored by EW precision tests & LHC searches ✗ FAROUGHY, GRELJO, KAMENIK (2016); FERRUGLIO, PARADISI, PATTORI (2017)
$(C_{S_R}^{\tau}, C_{S_L}^{\tau})$	charged Higgs boson $H^{\pm}$ ✓
$(C_{V_L}^{\tau}, C_{S_R}^{\tau})$	$\mathrm{SU}(2)_L$-singlet vector leptoquark U_1 ✓
$(C_{V_L}^{\tau}, C_{S_L}^{\tau} = -4C_T^{\tau})$	$\mathrm{SU}(2)_L$-singlet scalar leptoquark S_1 ✓
$(\mathrm{Re}[C_{S_L}^{\tau} = 4C_T^{\tau}],$ $\mathrm{Im}[C_{S_L}^{\tau} = 4C_T^{\tau}])$	scalar $\mathrm{SU}(2)_L$-doublet leptoquark S_2 with CP-violating couplings ✓

see e. g. MB, CRIVELLIN, DE BOER, KITAHARA, MOSCATI, NIERSTE, NIŠANDŽIĆ (2018)

Status of the $B_c \to \tau\nu$ bound

Charged-Higgs enhancement of $\mathcal{R}(D^*)$, $\mathcal{R}(J/\psi)$ correlates with large NP effects in $B_c \to \tau\nu$

- **2016:** measured $\mathcal{R}(D^*)$ implied $\text{BR}(B_c \to \tau\nu) \sim 50\%$ in conflict with bound $\text{BR}(B_c \to \tau\nu) < 30\%$ derived from B_c lifetime

Alonso, Grinstein, Martin Camalich (2016); based on Beneke, Buchalla (1996)

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- **2018:** caveats of τ_{B_c} calculation pointed out which relaxed constraint to $\text{BR}(B_c \to \tau\nu) < 60\%$ MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

  confirmed by reassessment of τ_{B_c} theory prediction Aebischer, Grinstein (2021)

- **present:** recent data show reduced anomaly in $\mathcal{R}(D^*)$ Iguro (2022)

  ➢ $\text{BR}(B_c \to \tau\nu)$ safely small ✓ (but: conflict with large $\mathcal{R}(J/\psi)$)

- **future:** FCC-ee can place stringent direct limit on $B_c \to \tau\nu$ and test charged-Higgs effects in $\mathcal{R}(D^*)$ and $\mathcal{R}(J/\psi)$ Fedele, Helsens, Hill, Iguro, Klute, Zuo (2023)

Lepton flavor universality in baryonic decays

NP in $b \to c\tau\nu$ can also be tested in baryonic decays

$$\mathcal{R}(\Lambda_c) = \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell\nu)} \qquad \ell = e, \mu$$

LHCb 2022: $\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$

compare to SM prediction: $\mathcal{R}(\Lambda_c)_{\text{SM}} = 0.324 \pm 0.004$

- hints at under-abundance of τ leptons, although not yet conclusive
- consistent NP explanation of $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$?

The $\mathcal{R}(\Lambda_c)$ sum rule

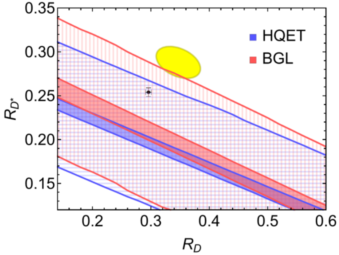
Approximate sum rule relating $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$

MB, Crivellin et al. (2018), (2019)
Fedele, MB et al. (2022)
Endo, Iguro, Mishima, Watanabe (2025)

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq \frac{1}{4}\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + \frac{3}{4}\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}$$

- originates in heavy-quark symmetry
- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c)$
- model-independent – holds for any NP in τ and/or light lepton channel
- can be extended to angular observables

Endo, Iguro, Kretz, Mishima, Watanabe (2025)



➢ **$\mathcal{R}(D^{(*)})$ anomaly testable with future LHCb measurements of $\mathcal{R}(\Lambda_c)$**

Further complementary probes of NP in $b \to c\tau\nu$

Restoring $SU(2)_L$ symmetry

- *recall:* left-handed fermions come in $SU(2)_L$ doublets
- NP in $b \to c\tau\nu$ generally linked to $b \to s\tau^+\tau^-$ and/or $b \to s\nu\bar{\nu}$
- pattern of NP effects can be used to determine NP operator structure

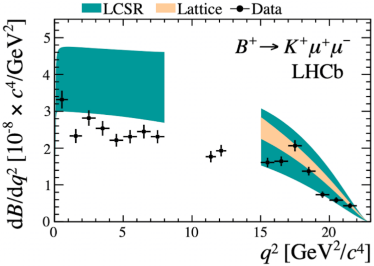
Relevant players

- B-meson staples: $B \to K^{(*)}\tau^+\tau^-$, $B_s \to \tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$ ...
- baryonic counterparts: $\Lambda_b \to \Lambda\tau^+\tau^-$, $\Lambda_b \to \Lambda\nu\bar{\nu}$ ...
- charming competitors? $B_c \to D_s^{(*)}\tau^+\tau^-$, $B_c \to D_s^{(*)}\nu\bar{\nu}$ ...

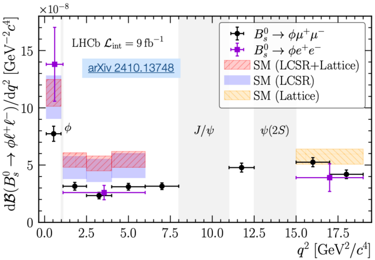
Anomalies in $b \to s\ell^+\ell^-$ decays

Branching ratios

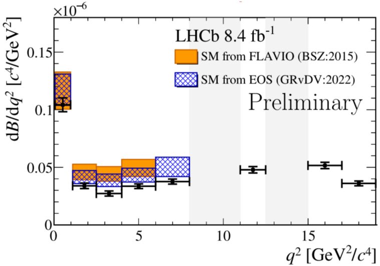
$B \to K\mu^+\mu^-$



$B_s \to \phi\ell^+\ell^-$

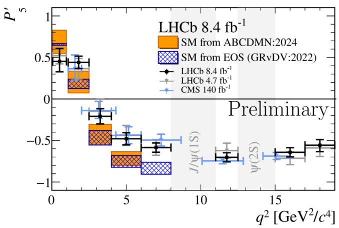


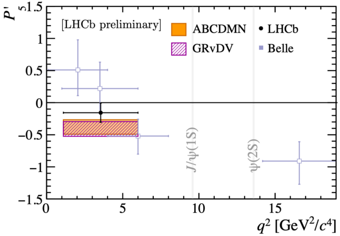
$B \to K^*\mu^+\mu^-$

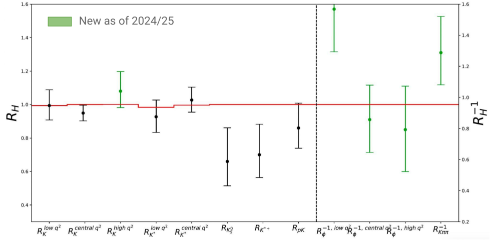


➢ consistent depletion below SM visible in low-q^2 region

Angular observables and lepton flavor universality







Theoretically cleaner observables in $b \to s\ell^+\ell^-$

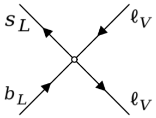
- $P_5'^{\mu}$ in tension with SM prediction, $P_5'^{e}$ consistent with both SM and $e-\mu$ universality
- less significant tensions also in other angular observables
- no indication for departure from $e-\mu$ universality

Global $b \to s\ell^+\ell^-$ fit

EFT picture

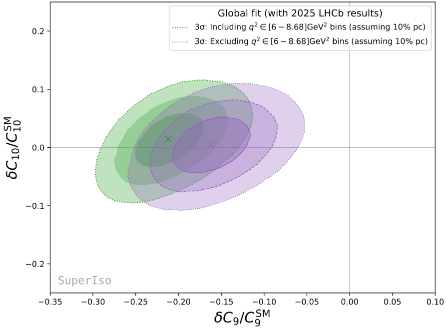
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$

- consistent fit to data for a $\sim -25\%$ shift in C_9



- $e - \mu$ universal effect

Hurth et al. (2025)



other recent fits e. g. Ciuchini et al. (2022); Gubernari et al. (2022)
Greljo et al. (2022); Alguero et al. (2023)

➢ can be scrutinized by **angular analysis of $\Lambda_b \to \Lambda\mu^+\mu^-$** Böer, Feldmann, van Dyk (2014)

NP interpretation of $b \to s\ell^+\ell^-$ anomaly

Tree or loop level?

- naive NP scale $\Lambda \sim 40\,\text{TeV}$ ➢ inaccessible even at FCC-hh
- loop-induced NP: scale lower by (at least) one order of magnitude: $\lesssim$ few TeV

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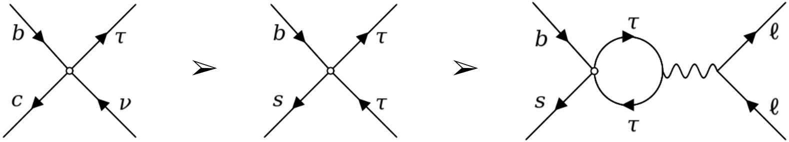
➢ **intriguing possiblity: link NP in $b \to s\ell^+\ell^-$ to $\mathcal{R}(D^{(*)})$ anomaly**

- NP mediating $b \to c\tau\nu$ can generate δC_9 via τ-loop
  - ➢ significant softening of $b \to s\ell^+\ell^-$ anomaly
  - ➢ large NP effects in $b \to s\tau^+\tau^-$ predicted

Bobeth, Haisch (2011); Bobeth et al. (2014)
Crivellin, Greub, Müller, Saturnino (2018)



Testing common NP hypothesis in Λ_b decays

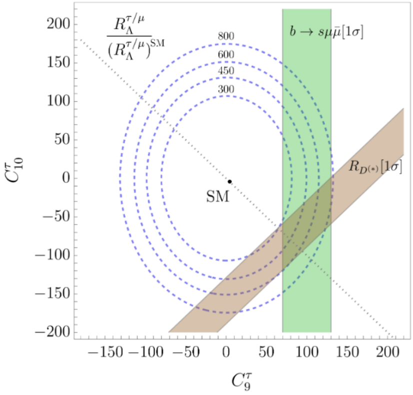
Lepton flavor universality in $\Lambda_b \to \Lambda\ell^+\ell^-$

- common origin of $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ anomalies predicts large τ/μ lepton flavor universality violation
- can be accessed in baryonic ratio

$$\mathcal{R}_\Lambda^{\tau/\mu} = \frac{\text{BR}(\Lambda_b \to \Lambda\tau^+\tau^-)}{\text{BR}(\Lambda_b \to \Lambda\mu^+\mu^-)}$$

enhanced w.r.t. SM prediction by two orders of magnitude!

- related channel: $\Lambda_b \to pK\tau^+\tau^-$



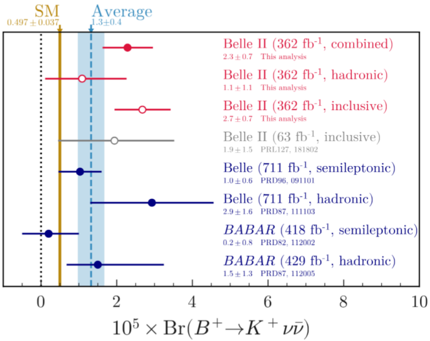
Bordone, Isidori, Mayer, Toelstede (2025)

New Physics in $b \to s\nu\bar{\nu}$?

Evidence for $B^+ \to K^+\nu\bar{\nu}$ decay

- Belle II: 2.7σ excess over SM value
- averaged data exhibits $\times 2.75$ enhancement (2σ tension)
- Belle upper limits

$$\text{BR}(B^0 \to K^{0*}\nu\bar{\nu}) < 1.8 \cdot 10^{-5}$$
$$\text{BR}(B^+ \to K^{+*}\nu\bar{\nu}) < 6.1 \cdot 10^{-5}$$



EFT picture:

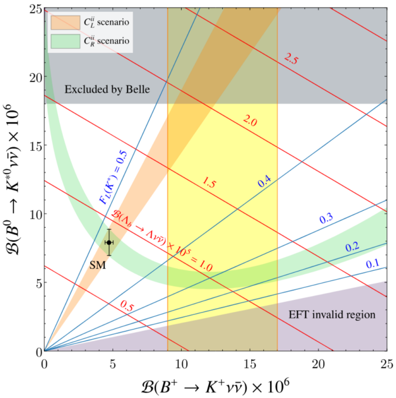
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha(M_Z)}{4\pi} C_L^{\text{SM}} \left[\sum_{i,j=1}^{3} \left((\delta^{ij} + C_L^{ij}) \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij} \right) \right]$$

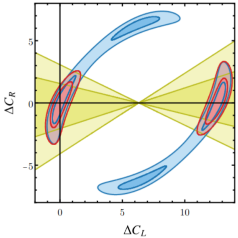
Impact on $\Lambda_b \to \Lambda\nu\bar{\nu}$

Disentangling NP in $b \to s\nu\bar{\nu}$

- $B \to K^{(*)}\nu\bar{\nu}$ sensitive to (axial)vector $b \to s$ current
  ➢ measuring both modes determines C_L, C_R
- complementary determination through longitudinal polarization fraction $F_L(K^*)$ and baryonic decay rate BR($\Lambda_b \to \Lambda\nu\bar{\nu}$)
- purely baryonic determination from BR($\Lambda_b \to \Lambda\nu\bar{\nu}$) and forward-backward asymmetry
  ➢ feasible at FCC-ee

Kitahara, Mohapatra, Sasaki (2026)





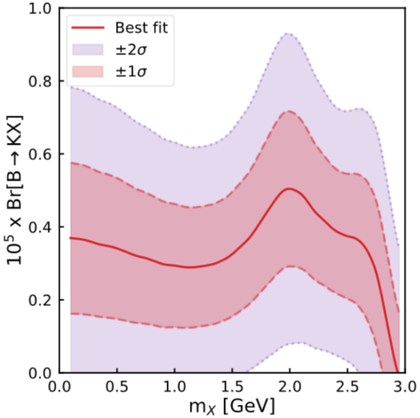
Altmannshofer, Gadam, Toner (2025)

A window to light NP

$B \to K\nu\bar{\nu}$ or $B \to K + X_{\text{invisible}}$?

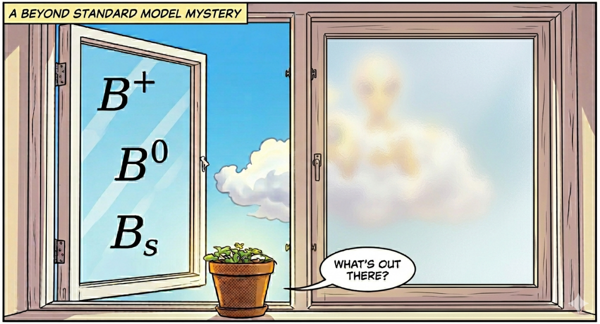
- experiment "observes" final-state neutrino pair as missing energy
- possibility for new light invisible particle(s)
  - sterile neutrinos
  - light dark matter
  - dark photon
  - axion-like particle

➢ impact on $b \to s + X_{\text{invisible}}$ differential decay rates
data shows slight preference for 2 GeV dark resonance



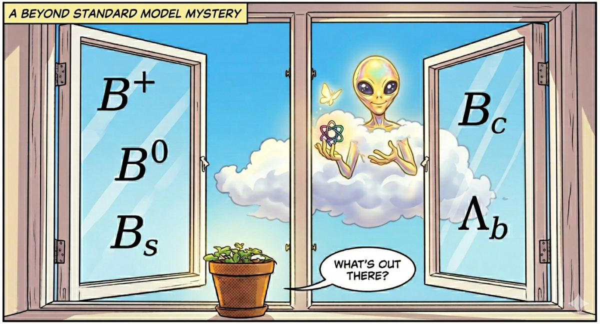
Altmannshofer, Crivellin, Haigh, Inguglia, Martin Camalich (2023)

Conclusions



b physics offers a powerful window to New Physics.

Conclusions



b physics offers a powerful window to New Physics.
B_c and Λ_b decays need to be included to exploit its full potential!