Recent news on the $\mathcal{R}(D^{(*)})$ anomaly

Monika Blanke

Karlsruher Institut für Technologie

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

KEK Theory Meeting on Particle Physics Phenomenology (KEK-PH2023)
KEK Tsukuba – November 7, 2023

New Physics, where are you?

Despite compelling arguments for New Physics (NP) at the TeV scale,
and despite more than a decade of very successful LHC operations,
we still **lack a discovery of new particles beyond the Standard Model** (SM)!

Where should we be looking?

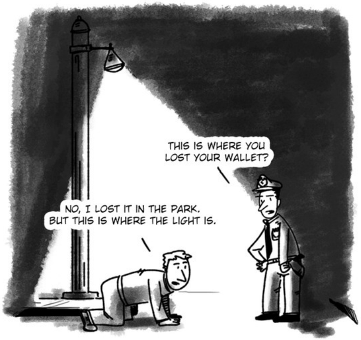
New Physics, where are you?

Despite compelling arguments for New Physics (NP) at the TeV scale,
and despite more than a decade of very successful LHC operations,
we still **lack a discovery of new particles beyond the Standard Model** (SM)!

Where should we be looking?

- observables with strong NP sensitivity
- clean theory prediction
- accessible to current experiments

➢ indirect NP searches in **precision observables** testing the SM **flavour sector**



Why lepton flavour universality tests?

Quark flavour violation

- present in the SM, but suppressed by small CKM mixing
- subject to non-perturbative uncertainties due to QCD confinement

Lepton flavour violation

- theoretically much cleaner, QCD effects often absent
- conserved in the SM, hence no interference with NP

Why lepton flavour universality tests?

Quark flavour violation

- present in the SM, but suppressed by small CKM mixing
- subject to non-perturbative uncertainties due to QCD confinement

Lepton flavour violation

- theoretically much cleaner, QCD effects often absent
- conserved in the SM, hence no interference with NP

Lepton flavour universality in quark flavour-violating decays

- theoretically clean, as hadronic uncertainties mostly cancel
- sizeable NP effects possible due to interference with SM

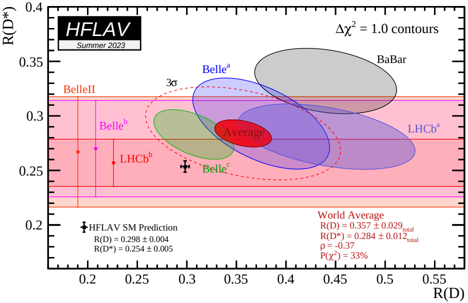
The $\mathcal{R}(D^{(*)})$ anomaly

Test of lepton flavour universality in semi-leptonic B decays

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

- theoretically clean, as hadronic and $|V_{cb}|$ uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb in decent agreement with each other
- LHCb found $\mathcal{R}(J/\psi)$ to be larger than expected in SM

➢ **persisting 3.3σ anomaly**
over-abundance of τ leptons



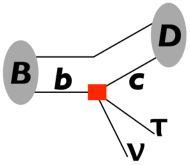
Effective Hamiltonian for $b \to c\tau\nu$

New Physics (NP) 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

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



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

Possiblle New Physics scenarios (tree level!)

$C^\tau_{V_L}$	vector $SU(2)_L$-triplet W' boson ➢ disfavoured by EW precision tests & LHC searches ✗ Faroughy, Greljo, Kamenik (2016); Ferruglio, Paradisi, Pattori (2017)
$(C^\tau_{S_R}, C^\tau_{S_L})$	charged Higgs boson $H^\pm$ ✓
$(C^\tau_{V_L}, C^\tau_{S_R})$	$SU(2)_L$-singlet vector leptoquark U_1 ✓
$(C^\tau_{V_L}, C^\tau_{S_L} = -4C^\tau_T)$	$SU(2)_L$-singlet scalar leptoquark S_1 ✓
$(\mathrm{Re}[C^\tau_{S_L} = 4C^\tau_T], \mathrm{Im}[C^\tau_{S_L} = 4C^\tau_T])$	scalar $SU(2)_L$-doublet leptoquark S_2 with CP-violating couplings ✓ see e. g. MB, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić (2018)

Beyond decay rates: $F_L^\tau(D^*)$

Belle 2018: first measurement of longitudinal D^* polarisation in $B \to D^* \tau \nu$

$$F_L^\tau(D^*) = 0.60 \pm 0.08 \pm 0.04$$

$\sim 1.7\sigma$ above SM expectation

Beyond decay rates: $F_L^\tau(D^*)$

Belle 2018: first measurement of longitudinal D^* polarisation in $B \to D^*\tau\nu$

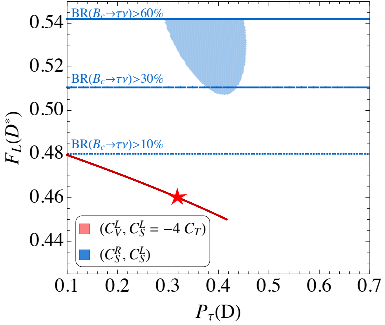
$$F_L^\tau(D^*) = 0.60 \pm 0.08 \pm 0.04$$

$\sim 1.7\sigma$ above SM expectation

Consequences for NP scenarios

- SM-like NP ($C_{V_L}^\tau$) does not affect polarisation observables
- charged Higgs can lift $F_L^\tau(D^*)$ into exp. 1σ range ✓
- leptoquark models have minor impact on $F_L^\tau(D^*)$
- tensor contribution C_T^τ leads to $F_L^\tau(D^*)$ suppression ✗

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)
Iguro, Kitahara, Omura, Watanabe, Yamamoto (2018)



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

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

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

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

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

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

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

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

- **2018:** caveats of τ_{B_c} calculation pointed out which relaxed constraint to 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)

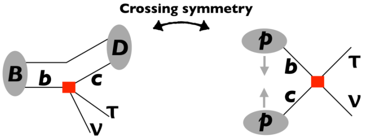
- **present:** recent LHCb and Belle data show reduced anomaly in $\mathcal{R}(D^*)$

  ➢ BR$(B_c \to \tau\nu)$ safely small ✓ Iguro (2022)

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

Complementary LHC searches

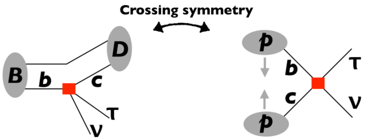
- crossing symmetry relates $b \to c\tau\nu$ to $pp \to X\tau\nu$
- mono-$\tau + \not{E}_T$ signature probes NP models for $\mathcal{R}(D^{(*)})$



➢ **EFT analysis: LHC has become competitive in testing NP behind anomaly**

Greljo, Martin Camalich, Ruiz-Alvarez (2018)

Complementary LHC searches



- crossing symmetry relates $b \to c\tau\nu$ to $pp \to X\tau\nu$
- mono-$\tau + \not{E}_T$ signature probes NP models for $\mathcal{R}(D^{(*)})$

➢ **EFT analysis: LHC has become competitive in testing NP behind anomaly**

Greljo, Martin Camalich, Ruiz-Alvarez (2018)

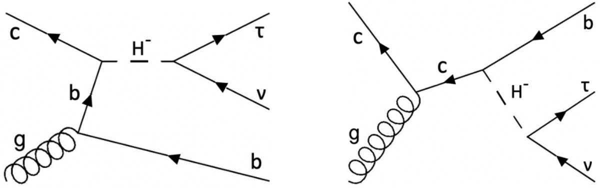
Charged Higgs in mono-τ final state

- charged Higgs produced as s-channel resonance
  ➢ significant deviation from EFT analysis
- mass-dependent constraint from recasting $W' \to \tau\nu$ searches
  ➢ charged Higgs solution to $\mathcal{R}(D^{(*)})$ ruled out for $m_{H^-} > 400$ GeV

Iguro, Omura, Takeuchi (2018)

What about a light charged Higgs?

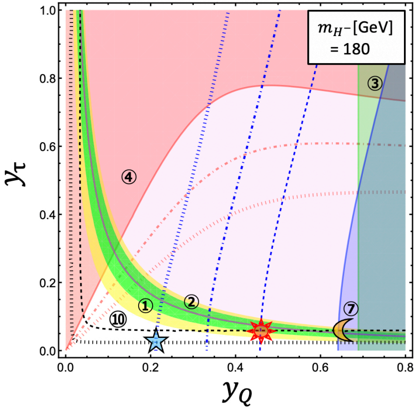
- light charged Higgs ($m_{H^-} < 400\,\text{GeV}$) not excluded by mono-$\tau$ data due to huge $W \to \tau\nu$ background
- efficient background suppression by requiring additional b-tagged jet



➢ **Is this sufficient to exclude the charged Higgs solution to the $\mathcal{R}(D^{(*)})$ anomaly?**

MB, Iguro, Zhang (2022)

Reach of the $b\tau\nu$ signature



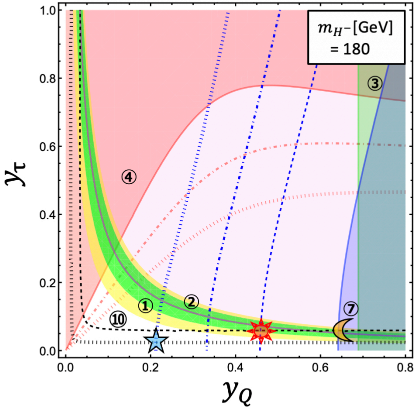
Minimal coupling scenario MB, Iguro, Zhang (2022)

($C^\tau_{S_L}$ only, additional couplings do not alter conclusions)

$$\mathcal{L}_{\text{int}} = +y_Q H^-(\bar{b}P_R c) - y_\tau H^-(\bar{\tau}P_L\nu_\tau)$$

- H^- close to top threshold most difficult to test
- relevant constraints from SUSY stau and (flavoured) dijet searches at the LHC Iguro (2022)

Reach of the $b\tau\nu$ signature



Minimal coupling scenario MB, Iguro, Zhang (2022)

($C^\tau_{S_L}$ only, additional couplings do not alter conclusions)

$$\mathcal{L}_{\text{int}} = +y_Q H^-(\bar{b}P_R c) - y_\tau H^-(\bar{\tau}P_L\nu_\tau)$$

- H^- close to top threshold most difficult to test
- relevant constraints from SUSY stau and (flavoured) dijet searches at the LHC Iguro (2022)
- performing (flavoured) dijet and **proposed $b\tau\nu$ search** with Run 2 data would *almost* exclude charged Higgs solution for $\mathcal{R}(D^{(*)})$
- **final verdict** from future LHC runs

Lepton flavour universality in baryonic decays

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

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

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)

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.280\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.720\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}$$

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c) = 0.324 \pm 0.004$
- consistent with expectation from heavy-quark symmetry
- model-independent – holds for any NP in τ lepton channel

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)

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.280\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.720\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}$$

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c) = 0.324 \pm 0.004$
- consistent with expectation from heavy-quark symmetry
- model-independent – holds for any NP in τ lepton channel

Model-independent prediction:

$$\mathcal{R}(\Lambda_c) \simeq 0.380 \pm 0.012_{\mathcal{R}(D^{(*)})} \pm 0.005_{\text{form factors}}$$

$\sim 2\sigma$ tension with LHCb measurement

Including NP in the light lepton modes

Step 1: check all possible two-particle scenarios (one coupling to τ, one to $\ell = e, \mu$)

- identified two scenarios capable of reproducing $\mathcal{R}(D)$, $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$:

$$S_1^\ell \ \& \ S_2^\tau \qquad\qquad S_1^\ell \ \& \ H^{\pm\tau}$$

- for both cases: $C_{V_L}^\ell \simeq -1$ (dest. interference with SM), $C_{S_L}^\ell = -8.9 C_T^\ell \simeq \pm 1$
  ➢ strongly incompatible with bounds from high-p_T observables, $B \to D^* \ell \nu$ angular distribution & polarisation observables, $B \to K^* \nu \bar{\nu}$, $|V_{cb}|$ fits ✗

Including NP in the light lepton modes

Step 1: check all possible two-particle scenarios (one coupling to τ, one to $\ell = e, \mu$)

- identified two scenarios capable of reproducing $\mathcal{R}(D)$, $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$:

$$S_1^\ell \ \& \ S_2^\tau \qquad\qquad S_1^\ell \ \& \ H^{\pm\tau}$$

- for both cases: $C_{V_L}^\ell \simeq -1$ (dest. interference with SM), $C_{S_L}^\ell = -8.9 C_T^\ell \simeq \pm 1$
  ➢ strongly incompatible with bounds from high-p_T observables, $B \to D^* \ell \nu$ angular distribution & polarisation observables, $B \to K^* \nu \bar{\nu}$, $|V_{cb}|$ fits ✗

Step 2: general 8dim NP fit including $C_{V_L}^\tau, C_{S_L}^\tau, C_{S_R}^\tau, C_T^\tau, C_{V_L}^\ell, C_{S_L}^\ell, C_{S_R}^\ell, C_T^\ell$

- viable fit to LFU ratios requires $C_{V_L}^\ell \simeq -1$, $C_T^\ell \simeq \pm 0.1$
- again excluded by high-p_T searches, $B \to D^* \ell \nu$ angular distribution & polarisation observables, $B \to K^* \nu \bar{\nu}$, $|V_{cb}|$ fits ✗

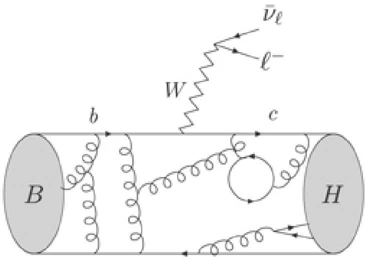
Fedele, MB, Crivellin, Iguro, Kitahara, Nierste, Watanabe (2022)

What about hadronic uncertainties?

"Naive" factorisation

- separation of scales in (RG-improved) theory
- factorisation of $B \to D^{(*)}\ell\nu$ decay rates into
  - perturbative weak interactions (+NP) contained in Wilson coefficients C_i
  - kinematical factors from phase-space intergral
  - non-perturbative strong interactions described by $\langle D^{(*)}|\mathcal{O}_i|B\rangle$ form factors

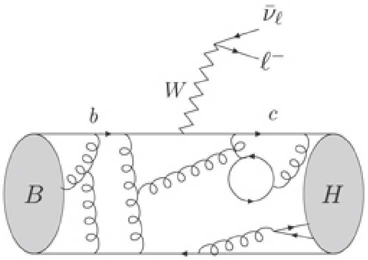
    ➢ major source of uncertainties



What about hadronic uncertainties?

"Naive" factorisation

- separation of scales in (RG-improved) theory
- factorisation of $B \to D^{(*)}\ell\nu$ decay rates into
  - perturbative weak interactions (+NP) contained in Wilson coefficients C_i
  - kinematical factors from phase-space intergral
  - non-perturbative strong interactions described by $\langle D^{(*)}|\mathcal{O}_i|B\rangle$ form factors
    ➢ major source of uncertainties



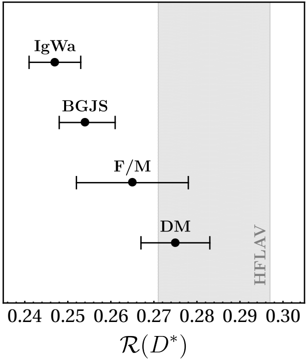
➢ Since form factors are independent of lepton flavour, the **ratios** $\mathcal{R}(D^{(*)})$ are **much less sensitive** to their uncertainties than the individual decay rates!

The issue with form factors

Finite τ lepton mass implies residual form factor dependence in LFU ratios $\mathcal{R}(D^{(*)})$

Form factor determinations

- **I**guro/**Wa**tanabe: based on improved HQET
- **B**igi/**G**ambino/**J**ung/**S**chacht: based on improved BGL
- **F**ermilab/**M**ILC: lattice + unitarity
- **D**ispersive **M**atrix: Fermilab/MILC + kinematic constraints Martinelli, Naviglio, Simula, Vittorio (2021)
- and others: HPQCD, JLQCD . . .



➢ **DM form factors significantly ameliorate tension in LFU ratios** (and incl./excl. $|V_{cb}|$)

DM form factors: all $b \to c\ell\nu$ anomalies gone?

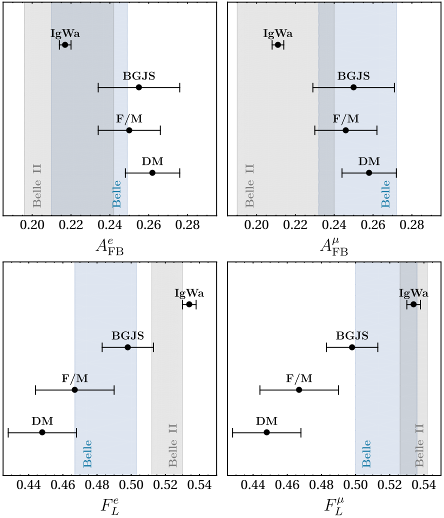
DM method constrains shape of form factors
➢ implies decreased $\mathcal{F}_1(w)$ at large recoil

General pattern

decreased form factor $\mathcal{F}_1(w)$ implies

- decrease in $d\Gamma^\ell/dw$ for $\ell = e, \mu$
  - ➢ larger extracted $|V_{cb}|$ ✓
  - ➢ increased $\mathcal{R}(D^*)$ ✓
- increase in forward-backward asymmetry A_{FB}^ℓ ✗
- decrease in longitudinal D^* polarisation F_L^ℓ ✗

Fedele, MB, Crivellin, Iguro, Nierste, Simula, Vittorio (2023)



Once again: New Physics in the light lepton modes?

Can New Physics in the light lepton modes address this emerging tension in F_L^ℓ?

- known from τ mode: significant deviations from SM require large contributions from scalar and/or tensor operators $C^\ell_{S_{L,R}}$, C^ℓ_T see e. g. Colangelo, de Fazio (2018)
- their interference with the SM contribution is proportional to the lepton mass m_ℓ and therefore strongly suppressed for light leptons

Once again: New Physics in the light lepton modes?

Can New Physics in the light lepton modes address this emerging tension in F_L^ℓ?

- known from τ mode: significant deviations from SM require large contributions from scalar and/or tensor operators $C^\ell_{S_{L,R}}$, C^ℓ_T see e. g. Colangelo, de Fazio (2018)
- their interference with the SM contribution is proportional to the lepton mass m_ℓ and therefore strongly suppressed for light leptons

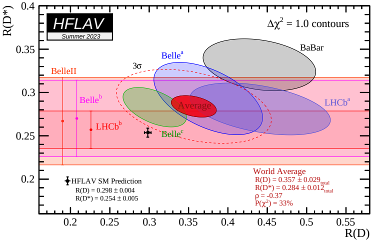
Longitudinal D^* polarisation F_L^ℓ with $\ell = e, \mu$

➢ is insensitive to New Physics ✗

➢ can be used to test form factor predictions against data:
emerging tension in F_L^μ hints at issue with DM form factors (or lattice input used)

Fedele, MB, Crivellin, Iguro, Nierste, Simula, Vittorio (2023)

Summary & outlook



$\mathcal{R}(D^{(*)})$ anomaly persists at the 3σ level

- status of NP analysis
  - charged Higgs solution preferred
  - testable at the (HL-)LHC
- challenged by baryonic decay data
  - sum rule: $\mathcal{R}(\Lambda_c)$ result inconsistent with $\mathcal{R}(D^{(*)})$
  - cannot be resolved by New Physics
- subject to form factor uncertainties: DM form factors
  - ameliorate $\mathcal{R}(D^{(*)})$ anomaly
  - create tension in F_L^ℓ: insensitive to NP, useful as experimental test of form factor calculations