Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

New physics in b-quark decays

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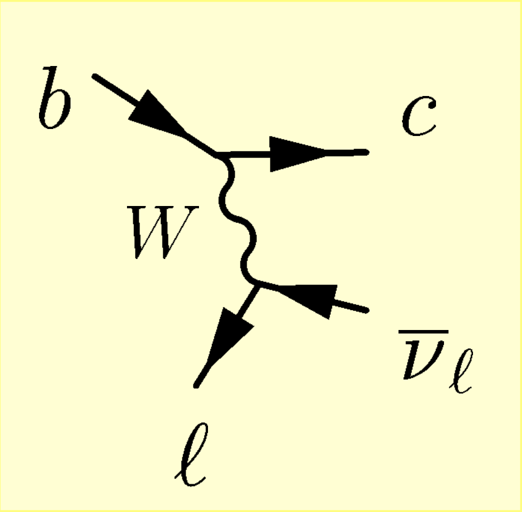
Flavour anomalies

In recent years several discrepancies between measurements (of branching ratios and/or angular decay distributions) and SM predictions have emerged, denoted as *flavour anomalies*.



This talk:

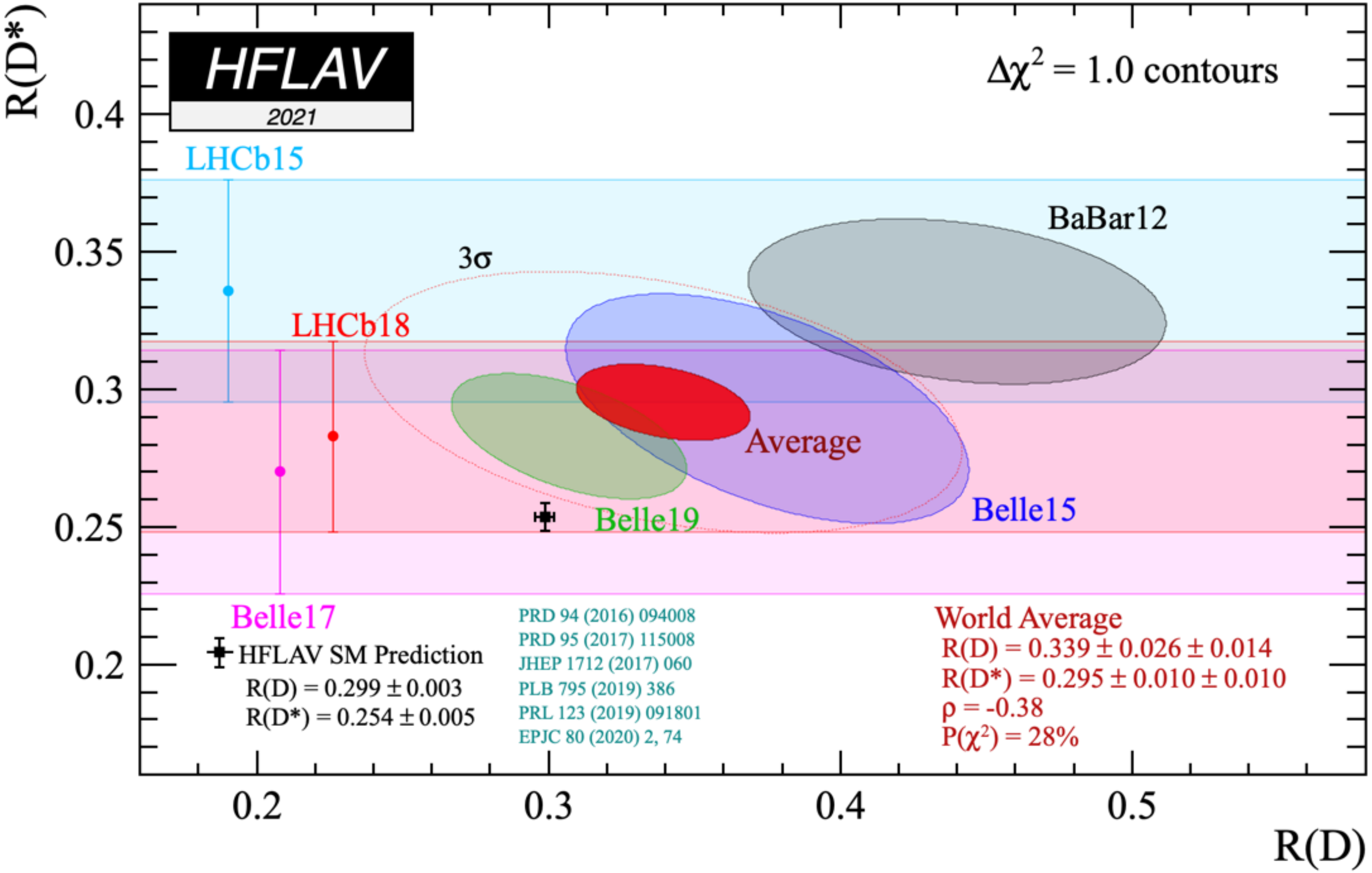
- $b \to c\tau\nu$: Enhancement of the ratios of branching ratios

$$R_D \equiv \frac{B(B \to D\tau\bar{\nu})}{B(B \to D\ell\bar{\nu})} \quad \text{and} \quad R_{D*} \equiv \frac{B(B \to D^*\tau\bar{\nu})}{B(B \to D^*\ell\bar{\nu})} \quad \text{with} \quad \ell = e, \mu.$$

BaBar, Belle, LHCb

R_D and R_{D*} in 2021

- central values of R_D and R_{D*} above SM predictions in all measurements
- some tension in R_D between BaBar12 and Belle19.
- average 3.3σ off from SM

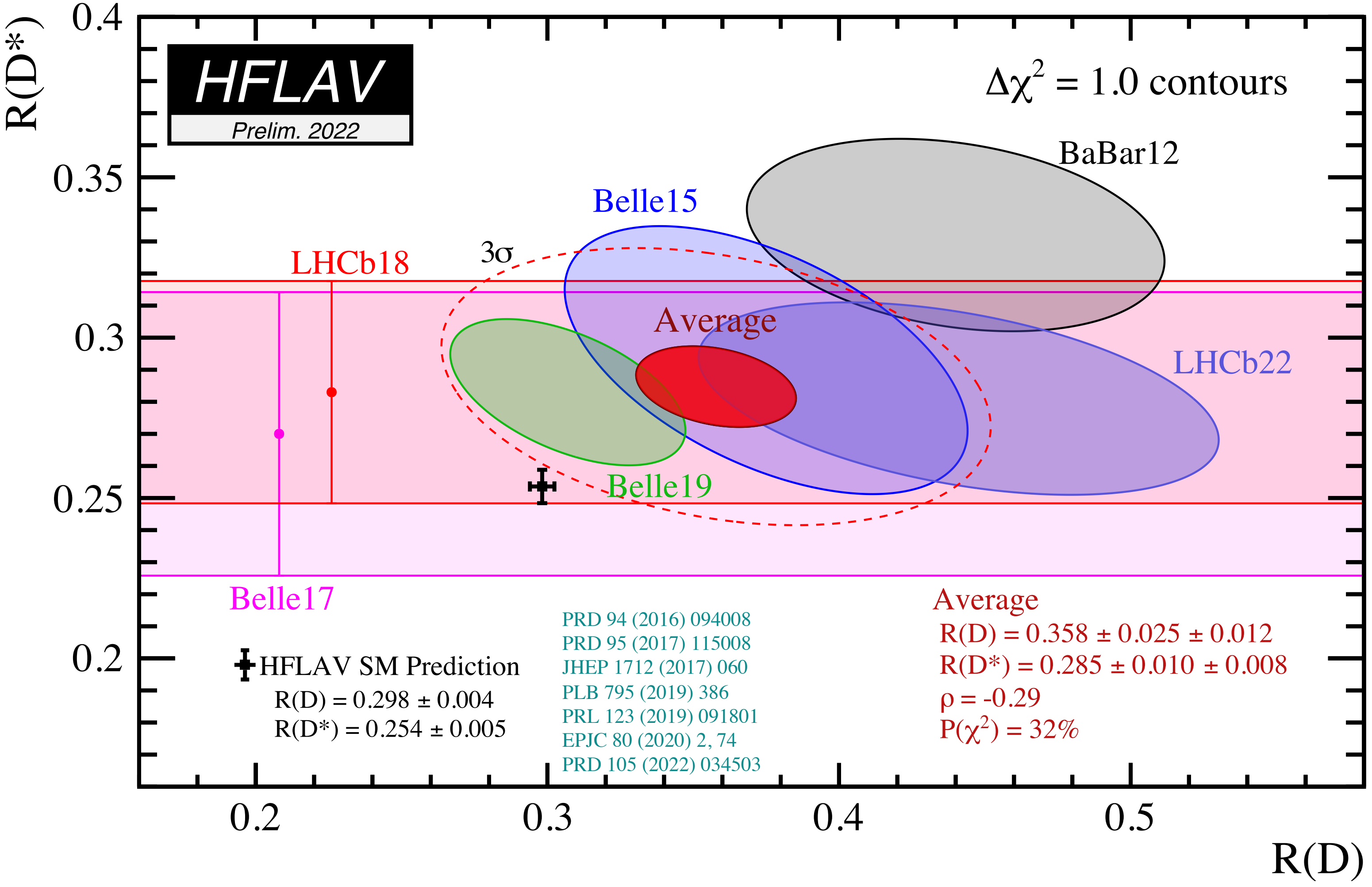


New LHCb measurement in 2022

- good overall agreement between experiments
  Note: $\Delta\chi^2 = 1$ ellipses correspond to p = 39% (while the horizontal strips correspond to p =68%)

- R_D larger, R_{D*} smaller

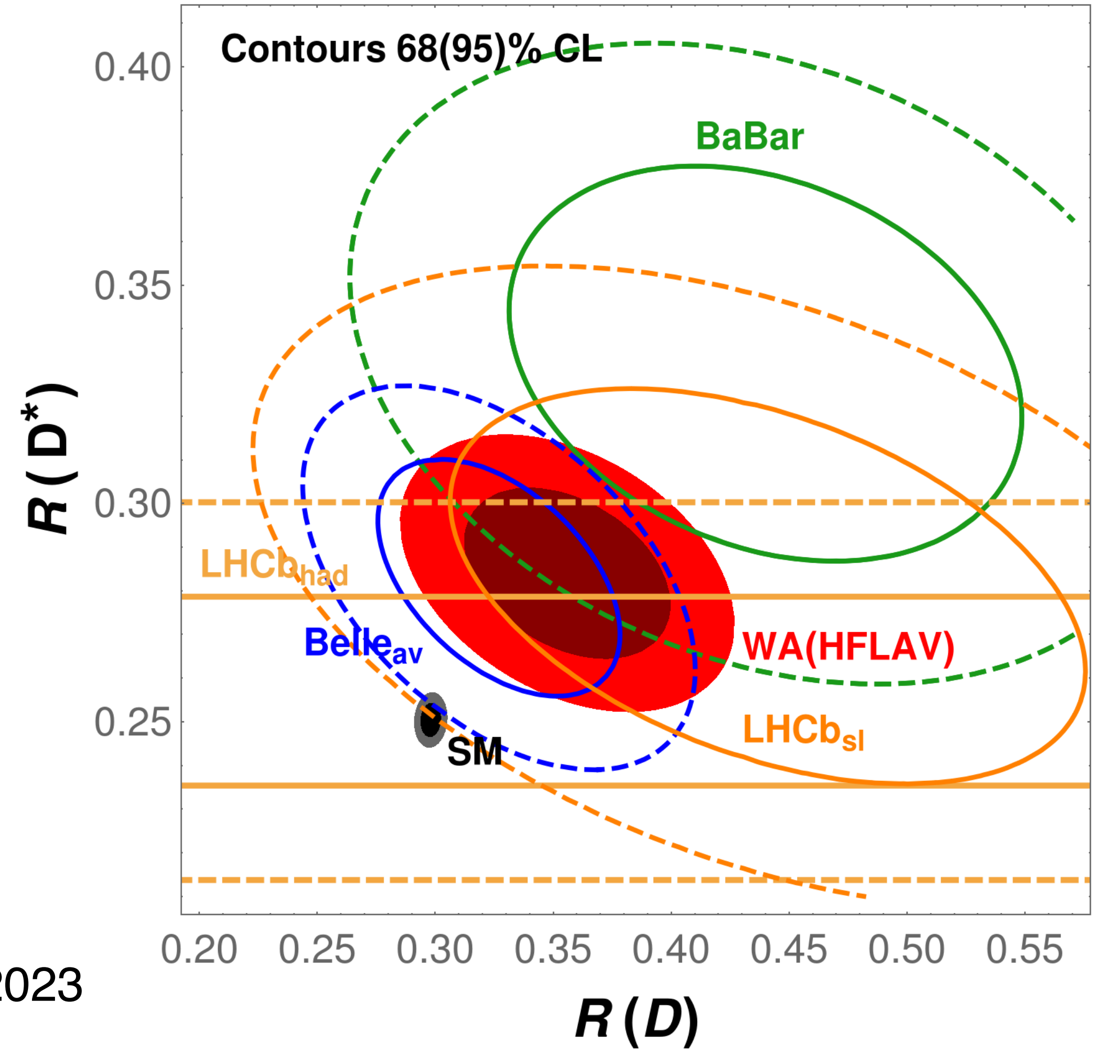
- average 3.2σ off from SM prediction



$R(D) - R(D^*)$ plot with 68%(95%) CL

- The 95% CL regions of all measurements overlap.

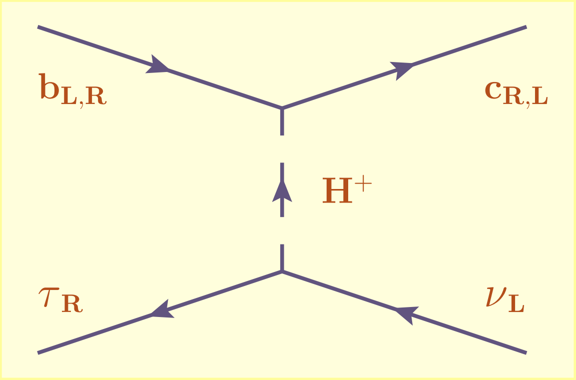
- Robust anomaly:
  - three experiments, different methods (semileptonic vs. hadronic tag)
  - SM prediction not contested



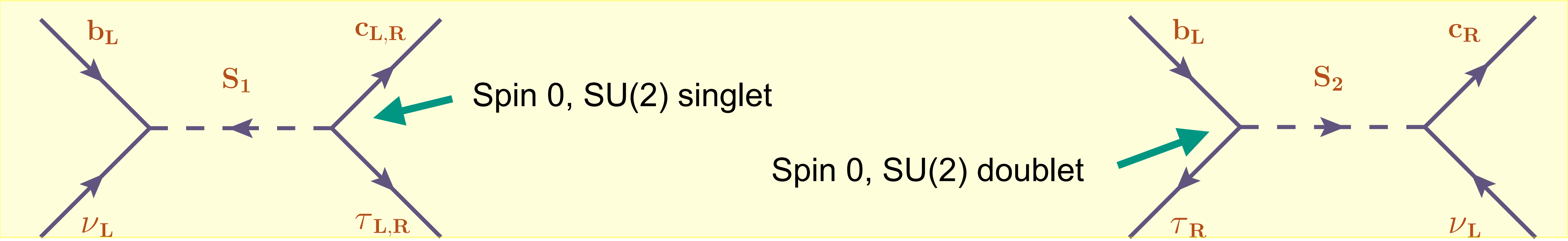
Plot from Judd Harrison, Martin Jung, *Beyond the Flavour Anomalies IV*, Barcelona 2023

New physics explanation

- Charged Higgs boson:
  was known to be sensitive to effects of a hypothetical charged Higgs boson since 1992.
  Grzadkowski,Hou, Phys. Lett. B **283** (1992) 427



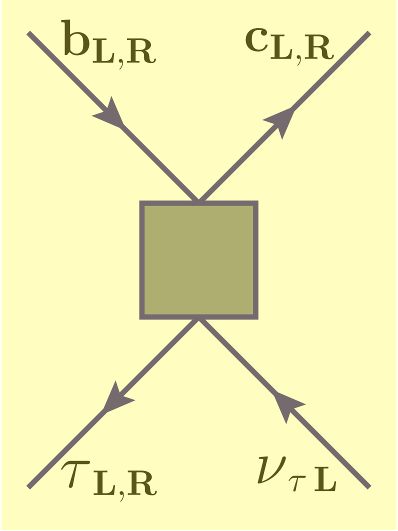
- Leptoquarks:
  - bosons with quark-lepton coupling
  - can also explain $(g-2)_\mu$ and $b \to s\mu^+\mu^-$ anomalies



  - appear in SU(4) gauge theories, where lepton number is the fourth colour

Effective operators

Nice: We can describe all types of new physics in terms of effective four-quark operators:



$$
\begin{aligned}
O_V^L &= \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_{\tau L} \,, \\
O_S^R &= \bar{c}_L b_R \, \bar{\tau}_R \nu_{\tau L} \,, \\
O_S^L &= \bar{c}_R b_L \, \bar{\tau}_R \nu_{\tau L} \,, \\
O_T &= \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \,.
\end{aligned}
$$

Fit the corresponding coefficients $C_V^L, C_S^{R,L}, C_T$ to data.

Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara,*Phys.Rev.D* 100(2019) 3, 035035

Iguro, Kitahara,Watanabe, arXiv:2210:10751

F_L^{D*}

Other input to global fit:

fraction of longitudinally polarised D^* in $B \to D^* \tau \bar{\nu}$:

$$F_L^{D*} = 0.60 \pm 0.08_{\mathrm{stat}} \pm 0.04_{\mathrm{sys}}$$ Belle 2019

$$F_L^{D*} = 0.464 \pm 0.003$$ SM prediction

This 1.4σ discrepancy has some effect on the global fit to the NP coefficients.

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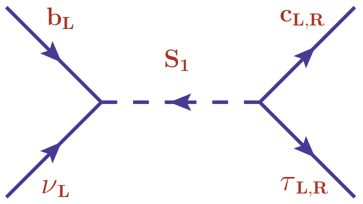
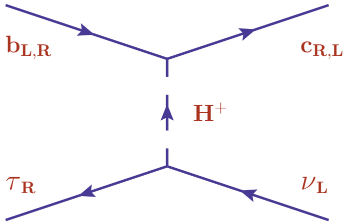
New-physics explanations

coefficients | motivated by

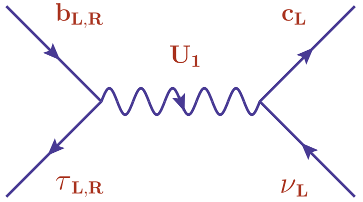
real $C_V^L,\ C_S^L = -4C_T$



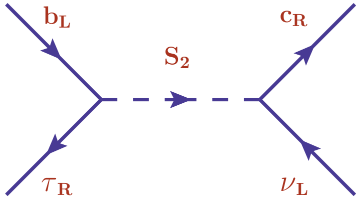
real $C_S^R,\ C_S^L$



real $C_V^L,\ C_S^R$



$\mathrm{Re}[C_S^L = 4C_T],\ \mathrm{Im}[C_S^L = 4C_T]$



All scenarios fit the $B \to D^{(*)}\tau\bar{\nu}$ data, with different predictions for $F_L(D^*)$ which is the fraction of decays with longitudinal D^* polarisation and $B(B_c^+ \to \tau^+\nu)$.

- H^+: larger $F_L(D^*)$ in better agreement with data.
- S_1: smaller (SM-like) $F_L(D^*)$.
- S_2: similar to H^+, but small $F_L(D^*)$, testable at ATLAS and CMS.

Charged-Higgs revival

- Before 2019: $R(D^*)$ called for sizable $\bar{c}\gamma_5 b \bar{\tau}_R \nu_{\tau L}$ coupling, i.e. sizable $C_R - C_L$. But this was in tension with the bound $B(B_c^+ \to \tau^+\nu) \leq 0.3$.

R. Alonso, B. Grinstein, J. Martin Camalich, Rev. Lett. 118, 081802 (2017)

“lose”

- In our 2018/2019 papers we found the fit to compromise between this tension and $F_L(D^*) > F_L(D^*)_{\mathrm{SM}}$, which the H^+ scenario can explain, while the leptoquark scenarios cannot.

Blanke et al.,*Phys.Rev.D* 100(2019) 3, 035035
Fedele et al., Phys. Rev. D107 (2023) 5, 055005

“tie”

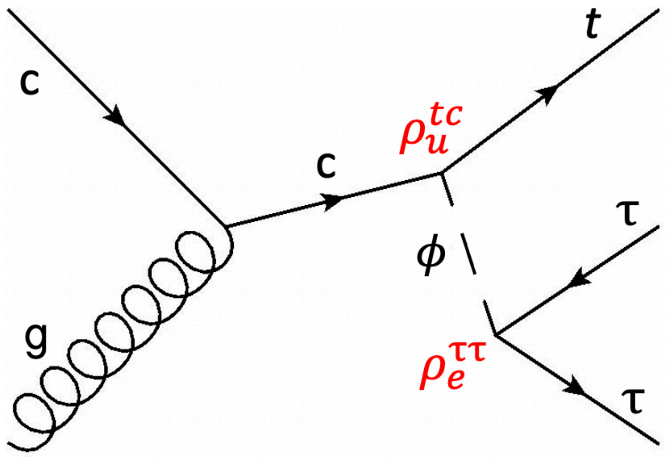
- The 2022 data shift the anomaly a bit from $R(D^*)$ to $R(D)$, so that the $B_c^+ \to \tau^+\nu$ is less relevant.

“win”

Charged-Higgs solution

- Girish Kumar, *Phys.Rev.D* 107 (2023) 7, 075016:
  Choose ad-hoc Yukawa sector
  $$L_{H^+} = \rho_{tc}(V_{tb}\bar{c}_R b_L + V_{ts}\bar{c}_R s_L)H^+ + \text{h.c.}$$
  and flavour-diagonal couplings to leptons to simultaneously explain $b \to c\tau\nu$ and $b \to s\ell\bar{\ell}$ anomalies and modify the W mass prediction.

- Critical test:
  Search for $cg \to t\tau^+\tau^-$ at LHC.
  Syuhei Iguro, *Phys.Rev.D* 107 (2023) 9, 095004.



τ polarisation asymmetry

Future:

$$P_\tau(D^*) = \frac{\Gamma(B \to D^* \tau^{\lambda=+1/2} \nu) - \Gamma(B \to D^* \tau^{\lambda=-1/2} \nu)}{\Gamma(B \to D^* \tau \nu)}$$

Belle 2017:

$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

Standard Model: $P_\tau(D^*) = -0.50 \pm 0.01$

Different NP explanations have different imprints on $P_\tau(D^*)$.

Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara,*Phys.Rev.D* 100(2019) 3, 035035

Iguro, Kitahara,Watanabe, arXiv:2210:10751

Sum rule for $b \to c\tau\bar{\nu}$

$R(D^*)$ and $R(D)$ are correlated with

$$R(\Lambda_c) = \frac{B(\Lambda_b \to \Lambda_c \tau \bar{\nu})}{B(\Lambda_b \to \Lambda_c \ell \bar{\nu})}\,,$$ where $\Lambda_b \sim bud, \quad \Lambda_c \sim cud$:

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.262\,\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\,\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} + x.$$

with $|x| < 0.05$ in any scenario of new physics.

Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara,*Phys.Rev.D* 100(2019) 3, 035035

What is behind the sum rule?

- In the heavy-quark limit $m_b \to \infty$:

$$B(B \to D^* \ell \nu) = 3B(B \to D \ell \nu)$$

 and

$$B(\Lambda_b \to \Lambda_c \ell \nu) = B(B \to D^* \ell \nu) + B(B \to D \ell \nu) = 1$$

- Thus $R(\Lambda_c) = \frac{1}{4}(3 - \epsilon)\, R(D^*) \;+\; \frac{1}{4}(1 + \epsilon)\, R(D)$ holds for all choices of ϵ. $\Rightarrow$ Optimise coefficients in

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} + x.$$

 to minimise x for all values of coefficients $C_V^L, C_S^{R,L}, C_T$ complying with data.

Sum rule for $b \to c\tau\bar{\nu}$

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} = 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} + x.$$

Our 2019 prediction (confirmed in 2022 with new data on $R(D^{(*)})$):

$$R(\Lambda_c) = R_{\rm SM}(\Lambda_c)\,(1.15 \pm 0.04) = 0.38 \pm 0.01 \pm 0.01$$

Tension with 2022 measurement by LHCb:

$$R(\Lambda_c) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$$

(LHCb, *Phys.Rev.Lett.* 128 (2022) 19, 191803)

→ with future data either $R(D^{(*)})$ will come down or $R(\Lambda_c)$ will go up.

Sum rule for $b \to c\tau\bar{\nu}$

Consider scenarios with only one particle contributing to $b \to c\tau\bar{\nu}$:

	scenario	$\mathcal{R}(D)$	$\mathcal{R}(D^*)$	$\mathcal{R}(\Lambda_c)$
	exp.	$0.36(3)$	$0.29(1)$	$0.24(7)$
SU(2) singlet leptoquark	S_1	$0.36(3)$	$0.29(1)$	$0.38(3)$
SU(2) doublet leptoquark	S_2	$0.36(3)$	$0.28(1)$	$0.40(4)$
SU(2) triplet leptoquark	S_3	$0.33(2)$	$0.29(1)$	$0.38(2)$
charged Higgs boson	$H^\pm$	$0.36(3)$	$0.28(1)$	$0.36(2)$

fit results

Fedele, Blanke, Crivellin, Iguro, Kitahara, UN, Watanabe, Phys. Rev. D107 (2023) 5, 055005

Summary

- BaBar, Belle, and LHCb data consistently point to values of R_D and R_{D*} above their SM predictions, with a combined significance of 3.2σ.

- The new LHCb measurement of R_{Λ_c} points to $\sim 2\sigma$ inconsistent measurements of at least one of R_D, R_{D*}, or R_{Λ_c}, irrespective of the presence of BSM physics, because these quantities fulfill a sum rule.

  → Redundancy of B physics helps to disentangle BSM physics from mistakes.

- Global fits of R_D, R_{D*}, and F_L^{D*} give good results for the charged-Higgs and leptoquark interpretations, both with discovery prospects at CMS and ATLAS.