Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Anomalous $b \to c\tau\nu$ data: form factors, leptoquarks, and charged Higgs bosons

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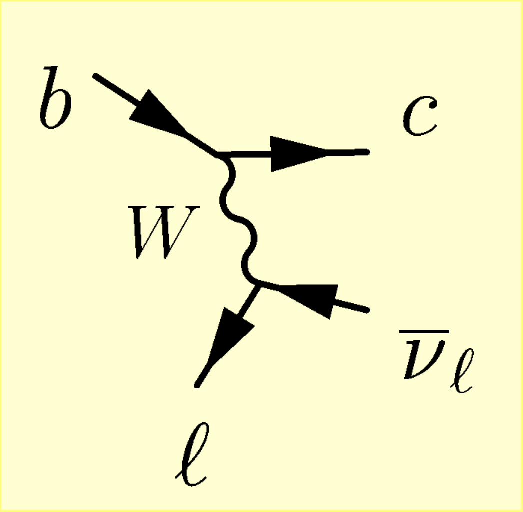
Flavour anomalies

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:

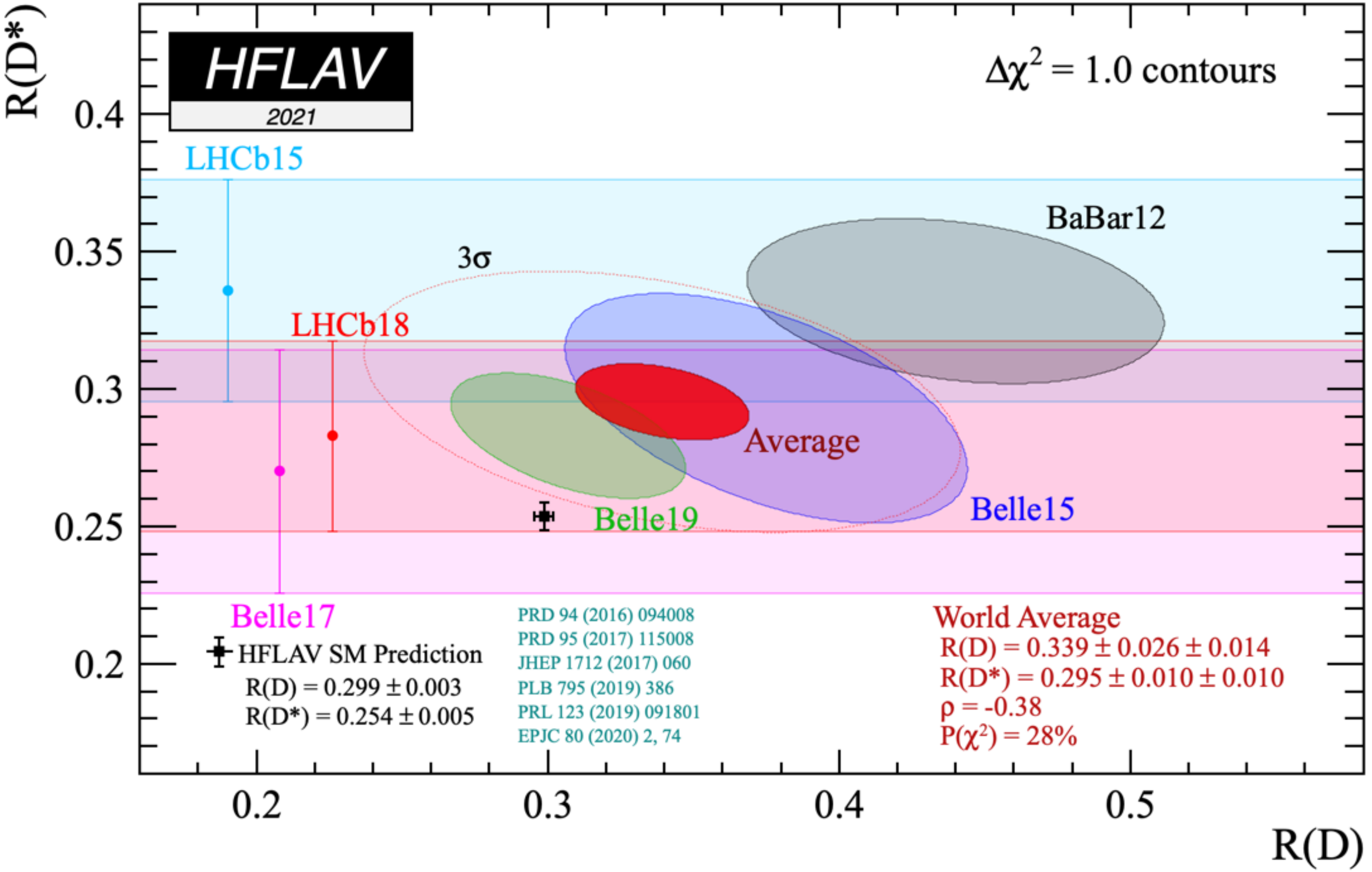
- $b \to c\tau\nu$: Enhancement of the ratios of branching ratios

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

BaBar, Belle, LHCb

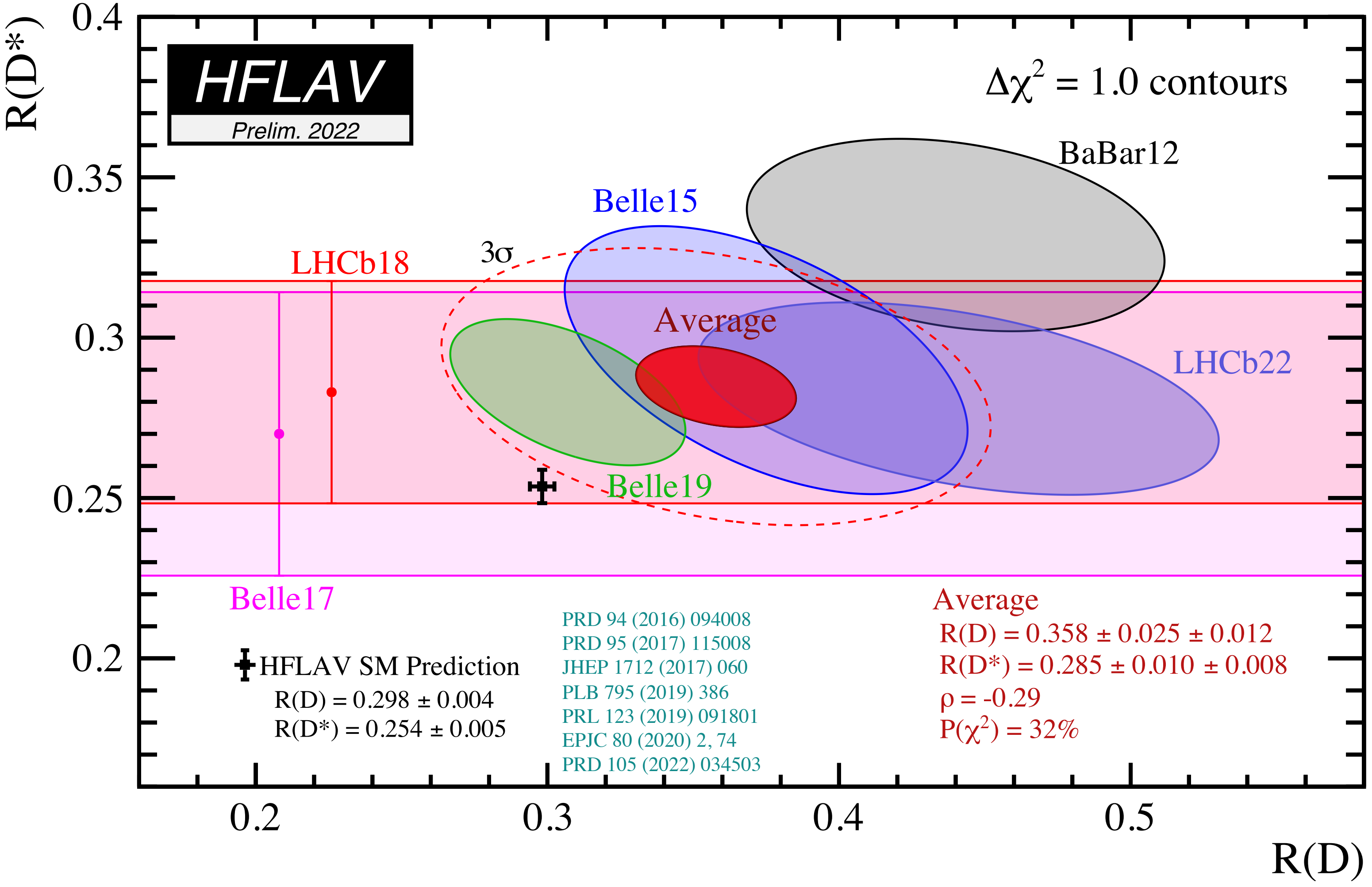
R_D and R_{D*} in 2021

- 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



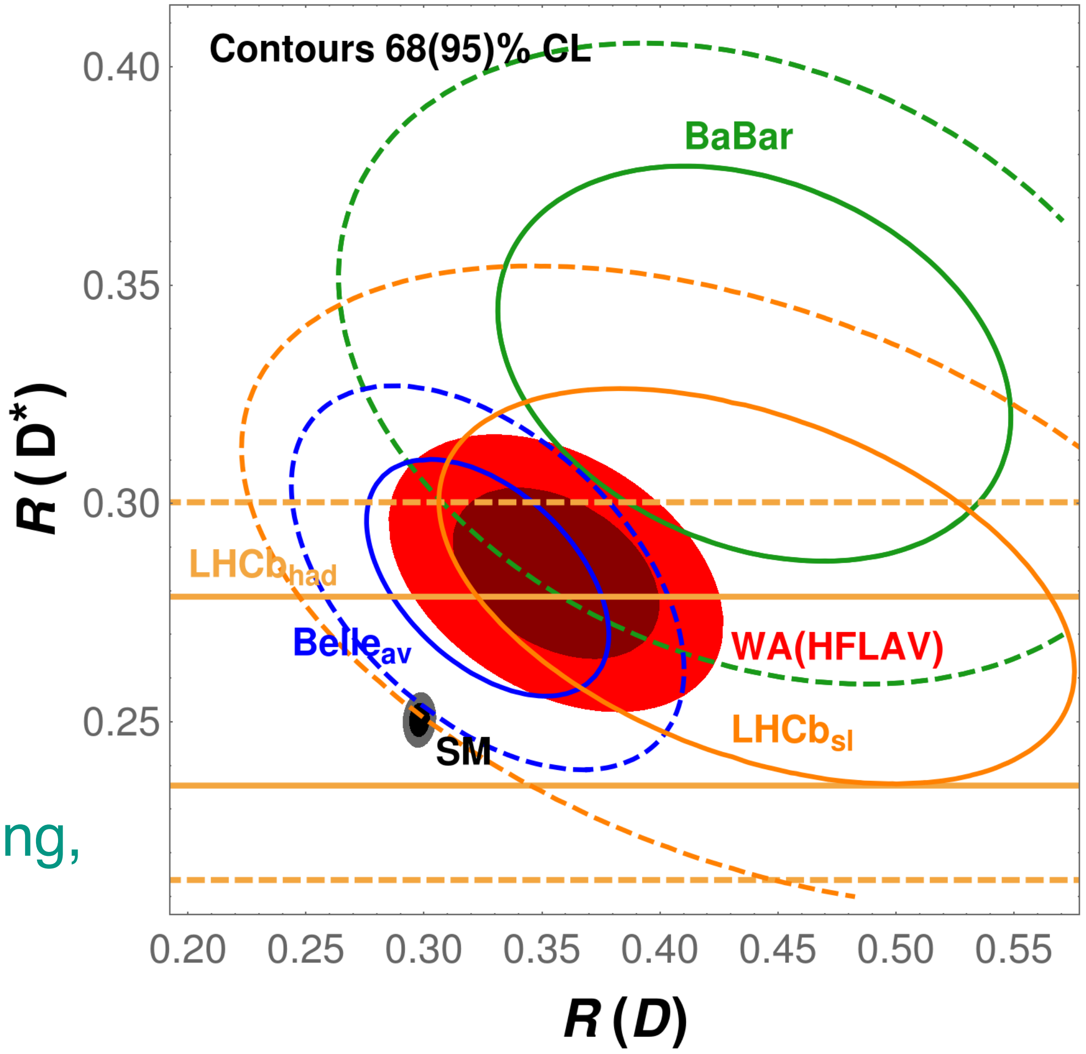
New LHCb measurement in 2022

- 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

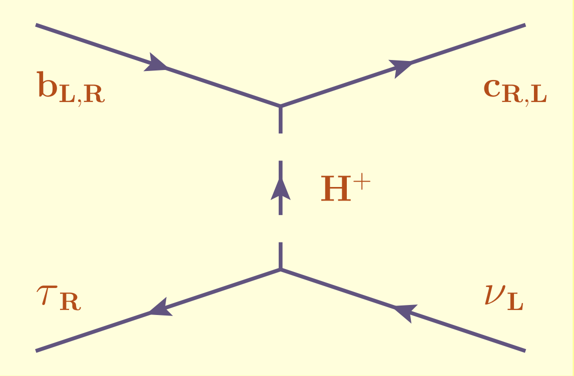
Plan of this talk:

- **Part I:**
  New physics in $b \to c\tau\nu$

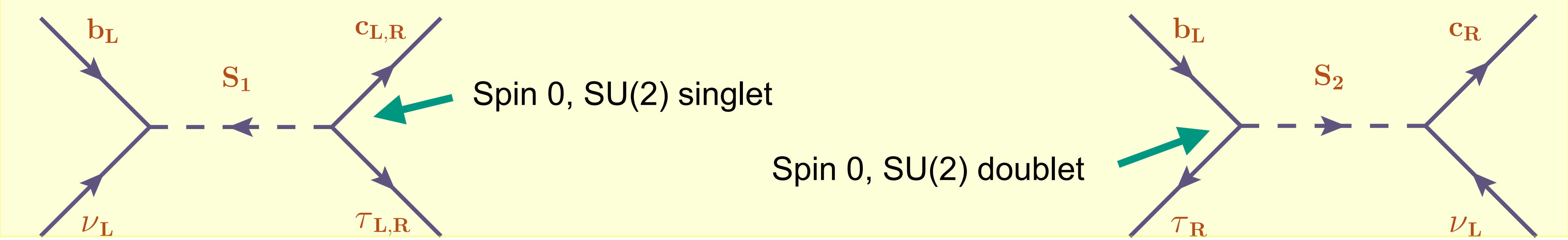
- **Part II:**
  Form factors and new physics in $b \to c\ell\nu$ with $\ell = e, \mu$

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



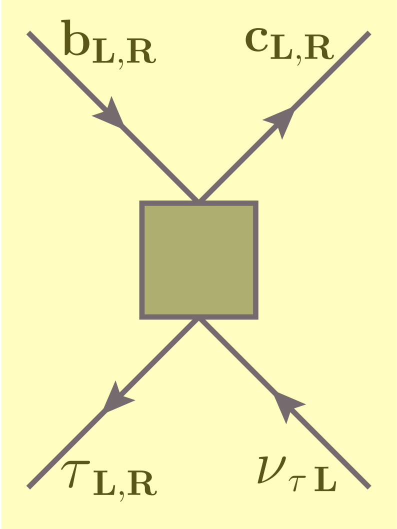
- Leptoquarks:
  - bosons with quark-lepton coupling
  - can also explain $(g-2)_\mu$ and $b \to s\mu^+\mu^-$ anomalies



  - 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 $B \to D^* \tau \bar{\nu}$:

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

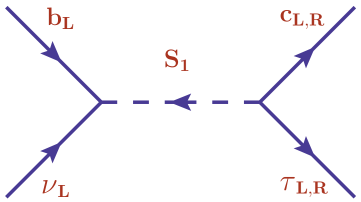
$$F_L^{D*} = 0.464 \pm 0.003$$ SM prediction

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

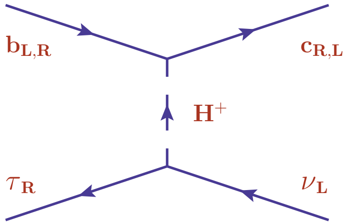
New-physics explanations

coefficients | motivated by

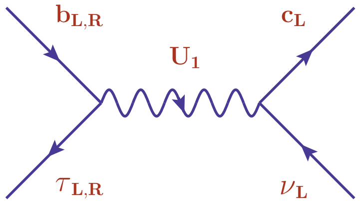
real $C_V^L,\ C_S^L = -4C_T$



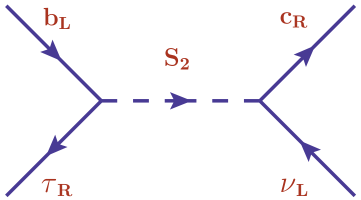
real $C_S^R,\ C_S^L$



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 $F_L(D^*) > F_L(D^*)_{\rm SM}$, 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 revival

Charged Higgs exchange feeds the coefficients $C_S^{L,R}$ of $O_S^L = \bar{c}_R b_L \bar{\tau}_R \nu_{\tau L}$ and $O_S^R = \bar{c}_L b_R \bar{\tau}_R \nu_{\tau L}$.

big

$$R(D) = R_{\rm SM}(D)\left[1 + 1.54\,\text{Re}\,(C_S^L + C_S^R)\right]$$

$$R(D^*) = R_{\rm SM}(D^*)\left[1 + 0.13\,\text{Re}\,(C_S^R - C_S^L)\right]$$

small

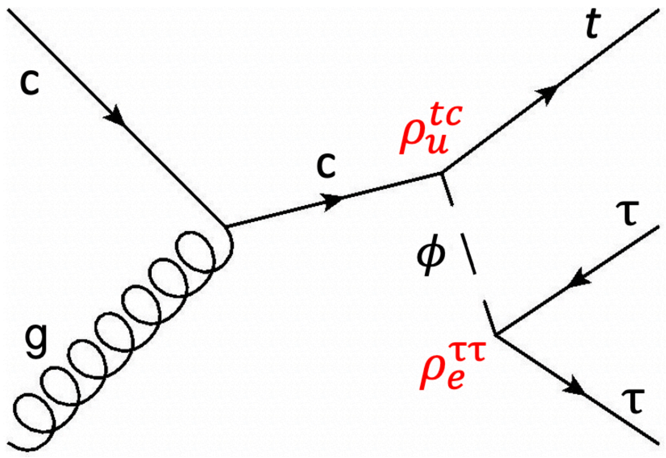
2022 LHCb result with larger $R(D)$ and smaller $R(D^*)$ corroborates the charged-Higgs interpretation

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

Part II: Form factors and new physics in $b \to c\ell\nu$ with $\ell = e, \mu$

Form factors

What I told you in Part I:

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

not quite true…

$B \to D^*$ form factors

For the Standard-Model prediction need

$$\langle D^*(p,\epsilon)\,|\,\bar{c}_L \gamma^\mu b_L\,|\,\bar{B}(p_B)\rangle,$$

which is expressed in terms of $(p+p_B)^\mu$, $q^\mu \equiv p_B^\mu - p^\mu$, ϵ^μ, and $\epsilon^\mu_{\nu\rho\sigma}\epsilon^\nu p^\rho q^\sigma$.

The coefficients involve four form factors, calculated with lattice QCD near $q^2 = q^2_{\max}$ and with QCD sum rules near $q^2 = 0$.

z expansion:

express form factors in powers of $z \equiv \dfrac{\sqrt{t_+ - t} - \sqrt{t_+ - t_-}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_-}}$

with $t \equiv q^2$, $t_\pm \equiv (m_B \pm m_D)^2$.

$B \to D^*$ form factors

Compare

BGL (Boyd, Grinstein, Lebed 1995):

global fit by Gambino, Jung, Schacht in 2019 to all available calculations and data in $B \to D^* \ell \nu$ with light leptons $\ell = e, \mu$. Phys. Lett. B 795 (2019) 386

HQET (using expansions in $\Lambda_{\rm QCD}/m_{c,b}$):

global fit by Iguro, Kitahara and Watanabe in 2022 to all available calculations and data (including q^2 shapes) in $B \to D^* \ell \nu$ with light leptons $\ell = e, \mu$. arXiv:2210.10751

Fermilab/MILC (2021):

first lattice calculation employing $q^2 \neq q^2_{\rm max}$.

Eur. Phys. J. C 82 (2022) 1141, Eur.Phys.J.C 83, 21 (2023).

$B \to D^*$ form factors

DM (Dispersive Matrix approach, Rome lattice group):

uses Fermilab/MILC data and Rome calculation of susceptibility χ,

employs analyticity and unitarity constraints to derive two-sided bounds on form factors.

G. Martinelli, S. Simula, and L. Vittorio, Phys. Rev. D 104 (2021) 094512,
Eur. Phys. J. C 82 (2022) 1083, JHEP 08 (2022) 022.
G. Martinelli, M. Naviglio, S. Simula, and L. Vittorio, Phys. Rev. D 106 (2022) 093002.

With DM method find $R(D^*)$ compatible with Standard Model prediction and furthermore $|V_{cb}|$ from $B \to D^* \ell \nu$ consistent with $|V_{cb}|$ from inclusive $B \to X_c \ell \nu$ decays.

$B \to D^*$ form factors vs new physics

Next slides: confront all four form factor predictions with new data on

the fraction $F_L^{D^*,\text{light}}$ of longitudinally polarized D^* in $B \to D^* \ell \nu$

and

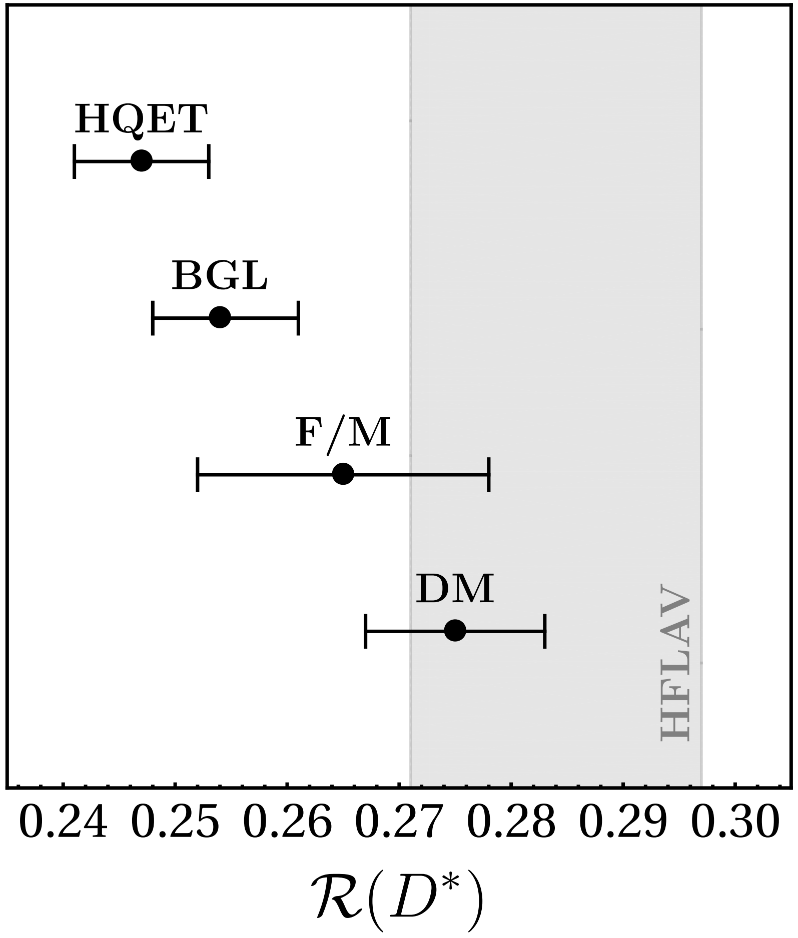
the forward-backward asymmetries A_{FB}^{e} and A_{FB}^{μ}

Belle, 2301.07529; Belle II, talk by Chaoyi Lyu at ALPS, March 2023

Discriminating $B \to D^* \ell \nu$ form factors via polarization observables and asymmetries

Fedele,Blanke,Crivellin,Iguro,UN,Simula,Vittorio, arXiv:2305.15457.

$B \to D^*$ form factors vs new physics



} compatible with Standard Model

with DM method one finds the same $R(D)$ as with other methods, arXiv:2205.13952

Predictions for $F_L^{D^*,\text{light}}$ and $A_{\text{FB}}^{e,\mu}$

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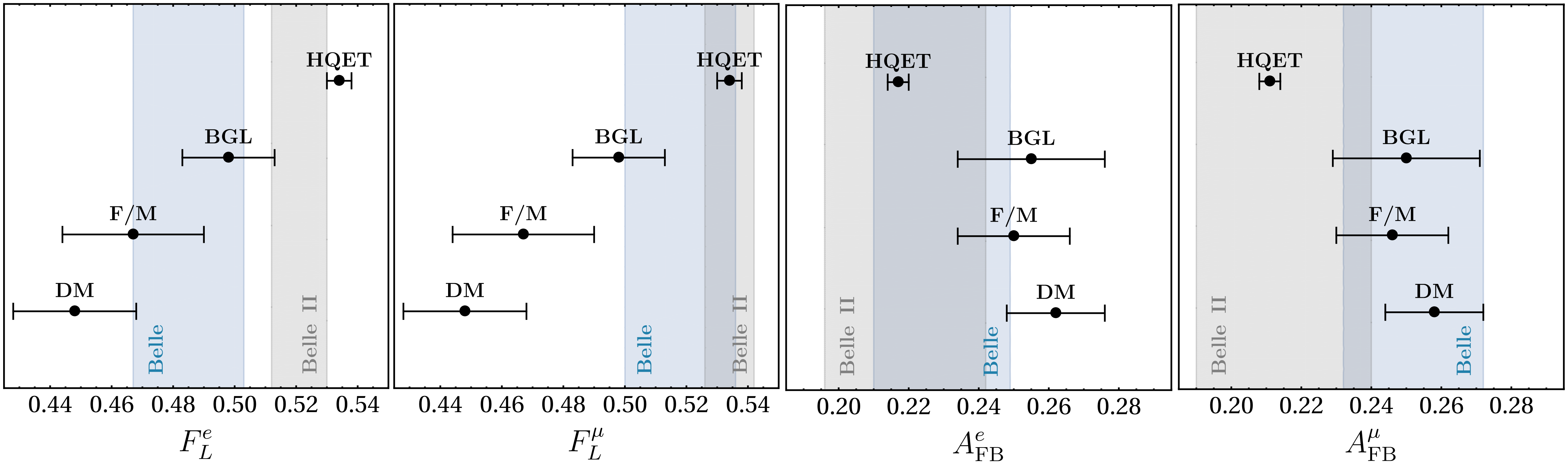


SM predictions with $\left\{ \begin{array}{l} \text{HQET or BGL} \\ \text{F/M or DM} \end{array} \right\}$ describe $\left\{ \begin{array}{l} B \to D^* \ell \nu \\ R(D^*) \end{array} \right\}$ data.

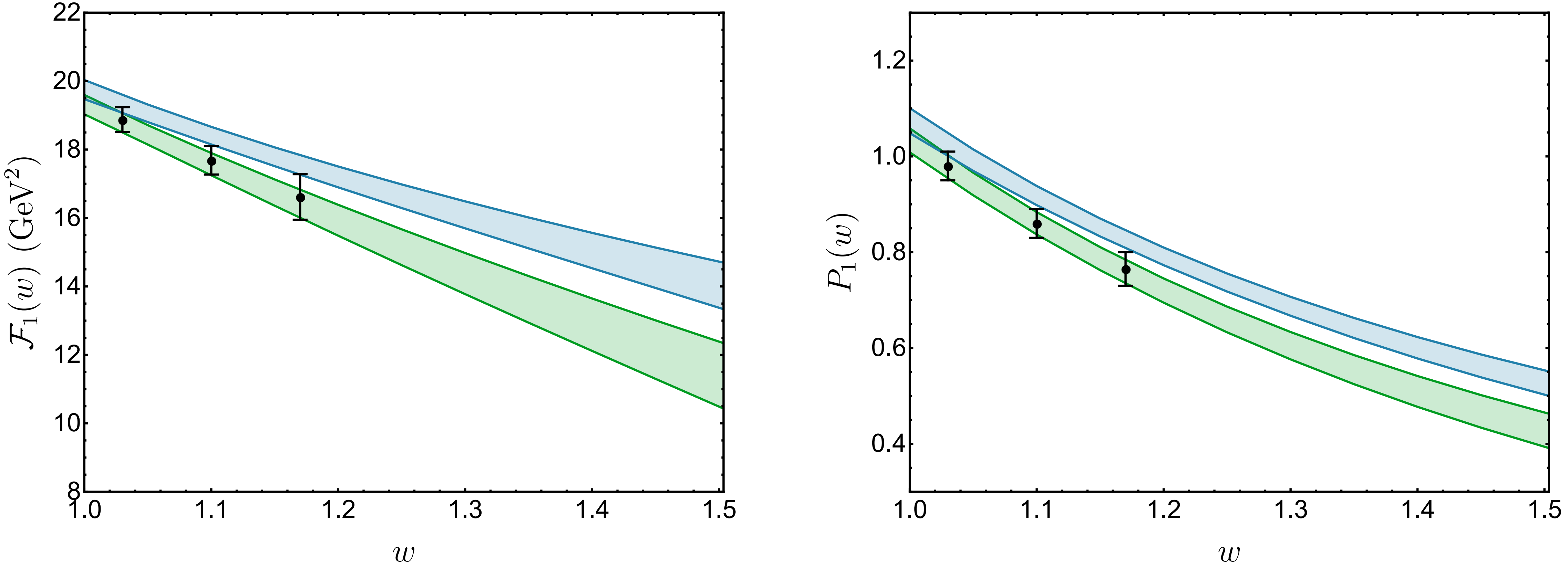
Form factors or new physics?

Next logical steps:

- perform a global fit to form factors including $F_L^{D^*,\text{light}}$ and $A_{\text{FB}}^{e,\mu}$, using the predicted form factors as priors,

- investigate whether there could be new physics in the $B \to D^* \ell \nu$ decays with light leptons $\ell = e, \mu$.

Global fit



Green: prior
Blue: posterior
Black: F/M error bars

$$w \equiv \frac{m_B^2 + m_{D*}^2 - q^2}{2 m_B m_{D*}}$$

DM form factors

DM fit result:

- compomise between $F_L^{D^*,\text{light}}$ and $R(D^*)$, thus tension with measured $R(D^*)$ as with other form factor predictons,
- post-fit $|V_{cb}| = 0.0412 \pm 0.0012$ from $B \to D^* \ell \nu$ branching fraction in good agreement with $|V_{cb}|_{\text{incl}}$, pre-fit $|V_{cb}| = 0.0431 \pm 0.0012$ is larger. (State-of-the-art determinations of $|V_{cb}|$ use more input beyond the branching fraction.)

DM form factors: new physics

New physics with scalar, tensor, or right-handed vector currents has no relevant impact on the $B \to D^* \ell \nu$ observables.

New physics decreasing the SM left-handed vector current coupling by 5% describes the data best, with $R(D^*)$ in perfect agreement with experiment. Only the DM form factors permit a solution to the $R(D^*)$ puzzle with new physics in the couplings to light leptons, while BGL, HQET, and F/M cannot.

But: new physics in left-handed vector current has zero effect on $F_L^{D^*,\text{light}}$, so the tension with DM stays.

→ $F_L^{D^*,\text{light}}$ is insensitive to any kind of new physics and is an excellent tool to check form factor calculations!

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.
- The 1.4σ excess in F_L^{D*} is best described by charged-Higgs hypothesis.
- New measurements of $F_L^{D*,\text{light}}$ disfavor form factor calculations using the dispersive-matrix approach with Fermilab/MILC data.
- $F_L^{D*,\text{light}}$ is insensitive to new physics and checks form factors.

Backup

Backup: form factor definitions

$$\langle D^*(p,\epsilon)|\bar c\gamma^\mu P_L b|\bar B(p_B)\rangle = \tag{8}$$
$$-\frac{V(q^2)}{m_B+m_{D^*}}\varepsilon^\mu_{\alpha\beta\gamma}\epsilon^{*\alpha}p^\beta q^\gamma + i\,A_0(q^2)\frac{m_{D^*}}{q^2}(\epsilon^*\cdot q)q^\mu$$
$$-\frac{iA_1(q^2)}{2(m_B-m_{D^*})}\left[(m_B^2-m_{D^*}^2)\epsilon^{*\mu}-(\epsilon^*\cdot q)(p+p_B)^\mu\right]$$
$$-\,iA_3(q^2)\frac{m_{D^*}}{q^2}(\epsilon^*\cdot q)\left[\frac{q^2}{m_B^2-m_{D^*}^2}(p+p_B)^\mu - q^\mu\right]\;,$$

with

$$2\,m_{D^*}A_3(q^2) = (m_B+m_{D^*})A_1(q^2)-(m_B-m_{D^*})A_2(q^2),$$

$$\begin{aligned} V(q^2) &= \frac{m_B+m_{D^*}}{2}g(w)\,,\\ A_1(q^2) &= \frac{f(w)}{m_B+m_{D^*}}\,,\\ A_2(q^2) &= \frac{1}{2}\frac{m_B+m_{D^*}}{(w^2-1)m_Bm_{D^*}}\left[\left(w-\frac{m_{D^*}}{m_B}\right)f(w)-\frac{\mathcal{F}_1(w)}{m_B}\right]\\ A_0(q^2) &= \frac{1}{2}\frac{m_B+m_{D^*}}{\sqrt{m_Bm_{D^*}}}P_1(w)\,, \end{aligned} \tag{10}$$

Recall: $w \equiv \dfrac{m_B^2+m_{D^*}^2-q^2}{2m_Bm_{D^*}}$

Backup: $F_L^{D^*,\mathrm{light}}$ and $A_{\mathrm{FB}}^{e,\mu}$

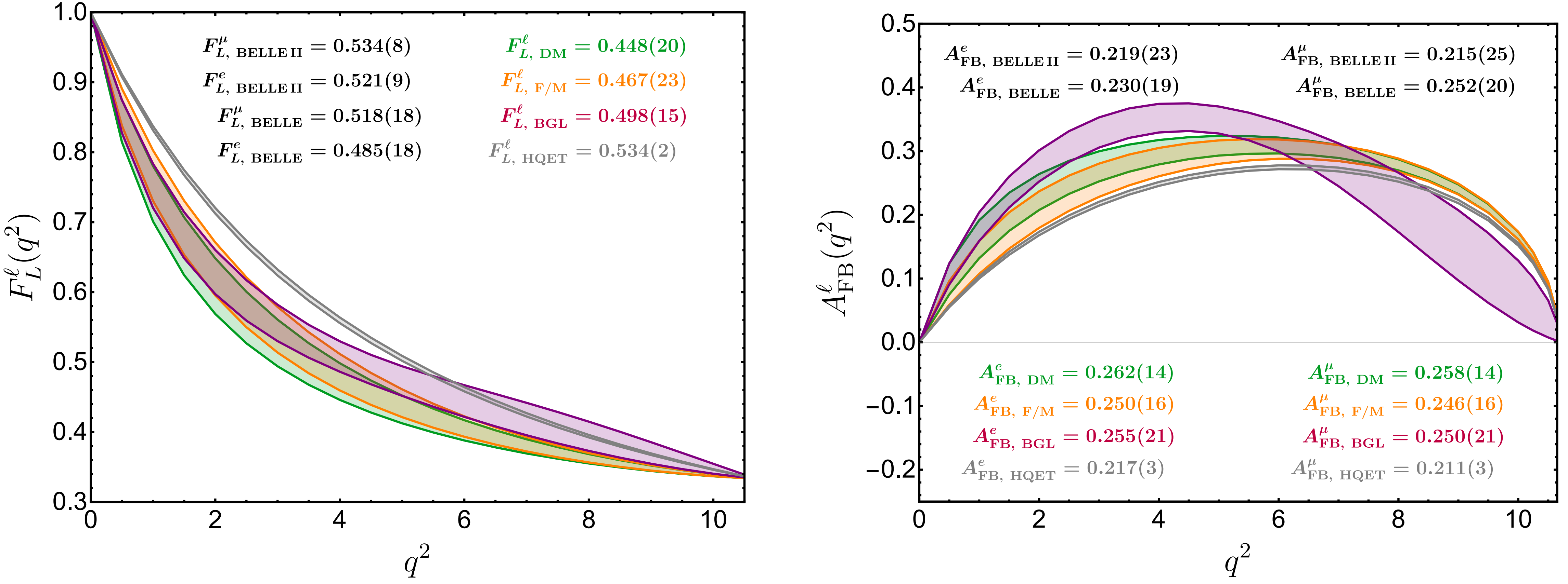


FIG. 2. Predicted $1\,\sigma$ range for F_L^ℓ (left panel) and A_{FB}^ℓ (right panel) as a function of q^2 for the four different FF sets.