A New Probe of the Nature of the B Physics Anomalies

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based on [StS, Soni: 2007.xxxx]

Where are we ~12yrs after LHC started?

- So far, the Standard Model works great.
- No big surprises at the LHC yet.
- Except for some anomalies in B decays !
  Seen @LHCb, Babar and Belle.

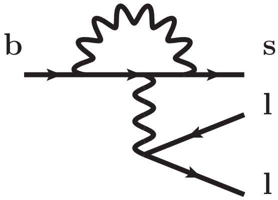
↳Tensions extremely interesting to explore completely.

A Crack in the Standard Model?

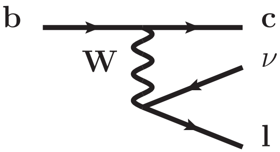
- Tensions could be just a statistical fluctuation.
- If not: 1) Problem in SM prediction or 2) BSM.
- In any case we will learn sth: about SM or BSM.
- Therefore, do everything to understand it.

B Anomalies

- There are anomalies in
  - flavor changing neutral current (FCNC) decays $b \to s l^+ l^-$
  - charged current decays $b \to c\tau\nu$.



Loop-level

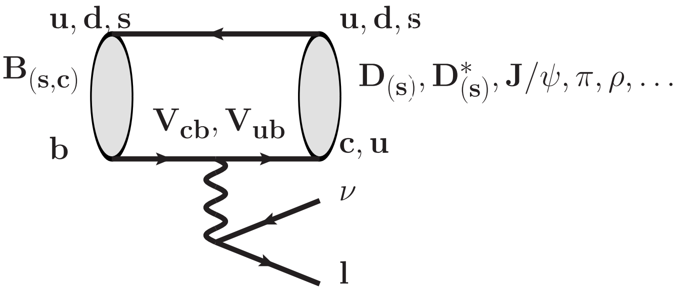


Tree-level

- This talk is about lepton flavor universality violation in charged currents.

What makes life harder

- Bound states of QCD introduce hadronic uncertainties.



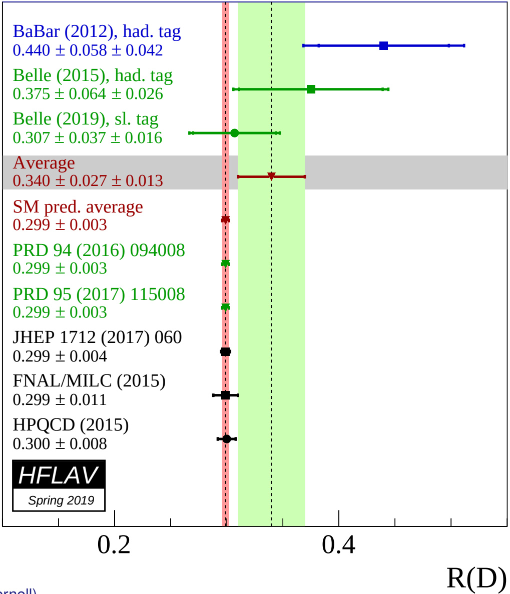
- The good thing:
  Decay modes w/ same underlying quark transition
  $\Rightarrow$ Cross-checks.

Lepton Flavor Nonuniversality

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}l\nu)} \qquad R\left(K^{(*)}\right) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

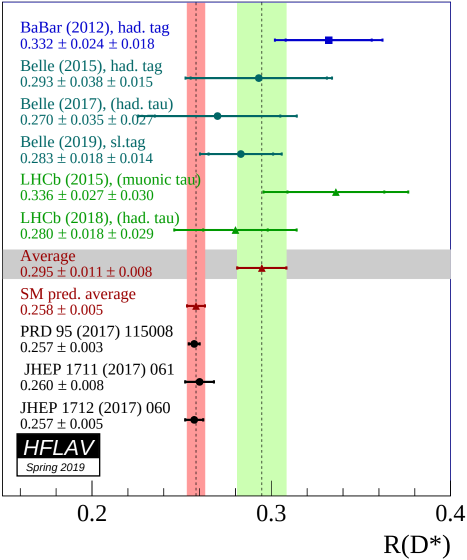
- Evidence for deviations of Lepton Flavor Universality.
- Hints for physics beyond the Standard Model. . .
- . . . however still below 5σ.
- Possible New Physics scenarios: New Scalars, Leptoquarks, W', ...
- Maybe connection between deviations in $b \to c$ and $b \to s$ transitions .

Status $R(D)$: 1.4σ [HFLAV 1909.12524]

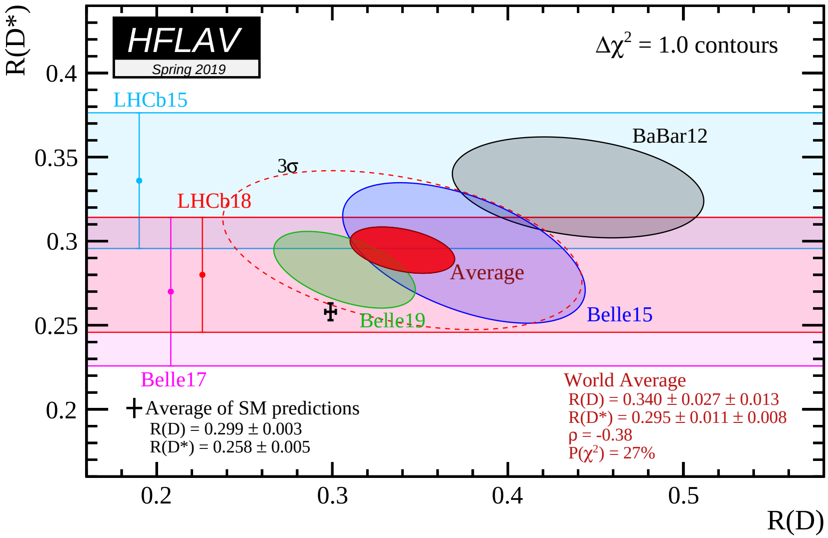


Status $R(D^*)$: 2.5σ [HFLAV 1909.12524]

[Bigi Gambino StS 1707.09509]



Status $R(D^{(*)})$ combined: 3.08σ [HFLAV 1909.12524]



New Player in the $b \to c\tau\nu$ Game: $B_c \to J/\psi\tau\nu$

Experiment [LHCb 1711.05623]

$$R(J/\psi)^{\mathrm{EXP}} = 0.71 \pm 0.17 \pm 0.18\,.$$

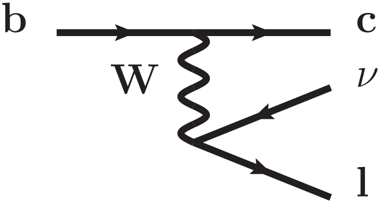
SM Theory [Murphy Soni 1808.05932, Cohen Lamm Lebed 1807.02730, 1909.10691]

$$R(J/\psi)^{\mathrm{SM}} = 0.25 \pm 0.03\,.$$

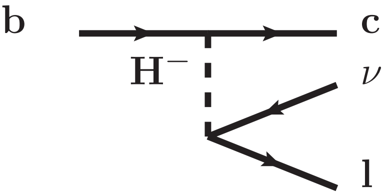
1.8σ, in same direction as $R(D^{(*)})$.

What could be the anomaly? Which new diagram?

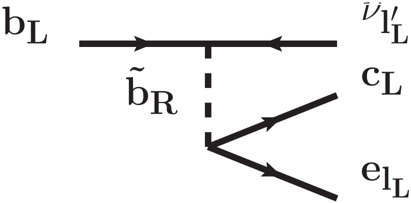
SM



charged Higgs ?



R-parity violating SUSY ?



[Altmannshofer Dev Soni Sui 2002.12910]

Effective Theory Classification

- Left-Handed Vector Model (rescaling of SM):

$$\mathcal{H}_{\text{eff}} \sim V_{cb}(1 + C_{V_L}) \left[(\bar{c}\gamma^{\mu} b_L) \left(\bar{l}_L \gamma_{\mu} \nu_{lL} \right) \right] .$$

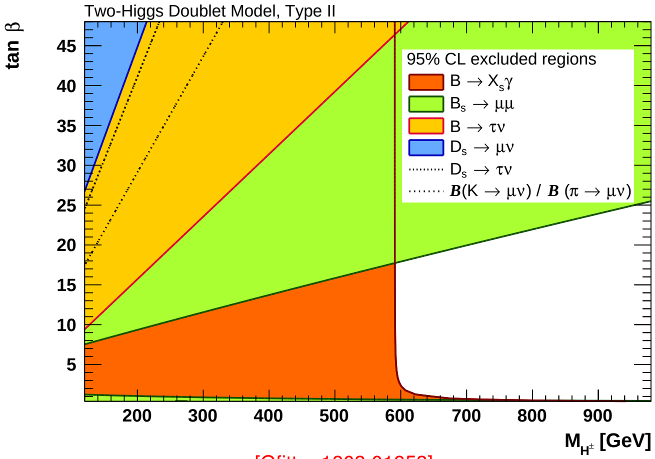
- Scalar Models:

$$\mathcal{H}_{\text{eff}} \sim V_{cb} C_{S_{L,R}} \left[(\bar{c} b_{L,R}) \left(\bar{l}_R \nu_{lL} \right) \right] .$$

What about a scalar in the new diagram?

- Challenging for 2HDM type I,II, noticed already by [Babar 1205.5442].
- More general 2HDMs with flavor-alignment can explain $R(D^{(*)})$

[Celis Jung Li Pich 1210.8443]



[Gfitter 1803.01853]

Many approaches to anomalies

Ways to differentiate models:

- Spectrum in invariant lepton mass q^2
- Angular observables.
- Models may need additional form factors.
- Comparison of decay channels, sum rules?

Multitude of $b \to c\tau\nu$ Decay Modes

$B_q \to V\tau\nu$
- $B \to D^*\tau\nu$
- $B_s \to D_s^*\tau\nu$
- $B_c \to J/\psi\tau\nu$

$B_q \to P\tau\nu$
- $B \to D\tau\nu$
- $B_s \to D_s\tau\nu$
- $B_c \to \eta_c\tau\nu$

and $B_c \to \tau\nu$.

$$R(D^*),\ R(D_s^*),\ R(J/\psi),\ R(D),\ R(D_s),\ R(\eta_c)\,.$$

Do we have generic predictions satisfied by all of these, depending on which type of NP?

Find out which diagram: Model-specific sum rule

Left-Handed Vector Models

[Greljo Isidori Marzocca 1506.01705]

$$\frac{R(D^*)}{R(D^*)^{\mathrm{SM}}} = \frac{R(D)}{R(D)^{\mathrm{SM}}} = \frac{R(V)}{R(V)^{\mathrm{SM}}} = \frac{R(P)}{R(P)^{\mathrm{SM}}} = \mathrm{const.}$$ for all decay modes.

Rescaling of SM couplings only.

If particle in new diagram not vector, sum rule violated.

E.g. R-parity violating SUSY model [Altmannshofer Dev Soni 1704.06659]

Is this valid for scalar models, too?

Find out which diagram: Model-specific sum rule

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Is this valid for scalar models, too?

NO.

Question of this talk:

Is there a similar relation for scalar models?

Find out which diagram: Model-specific sum rule

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NO.

Question of this talk:

Is there a similar relation for scalar models?

YES.

Summary of Introduction

- There are tensions in three $b \to c\tau\nu$ lepton flavor universality observables.

$$R(D^*) \qquad\qquad R(D) \qquad\qquad R(J/\psi)$$

- Which new diagrams could be responsible?
- Strategy in this talk:
  Find sum rules valid only in certain generic model.

Overview

- Anatomy of $R(V)$, $R(P)$ in SM and Scalar Models.
- Relation between $b \to c\tau\nu$ Decay Modes.
- Application to $R(V)$ and $R(P)$.
- Comparison to Data.

Anatomy of $R(V)$, $R(P)$ in SM

$$R(\{V,P\}) \equiv \frac{\int_{m_\tau^2}^{(m_{B_q}-m_{\{V,P\}})^2} dq^2\, d\Gamma_\tau/dq^2}{\int_0^{(m_{B_q}-m_{\{V,P\}})^2} dq^2\, d\Gamma_{\text{light leptons}}/dq^2}$$

Differential decay rate for $B_q \to \{V,P\}\tau\nu_\tau$

[BGL, hep-ph/9705252]

$$\frac{d\Gamma_\tau^V}{dq^2} = \left(1-\frac{m_\tau^2}{q^2}\right)^2\left(1+\frac{m_\tau^2}{2q^2}\right)\frac{d\Gamma^V_{\text{light leptons}}}{dq^2} + m_\tau^2\, P_1(q^2)^2 \times \text{phase space}\,,$$

$$\frac{d\Gamma_\tau^P}{dq^2} = \left(1-\frac{m_\tau^2}{q^2}\right)^2\left(1+\frac{m_\tau^2}{2q^2}\right)\frac{d\Gamma^P_{\text{light leptons}}}{dq^2} + m_\tau^2 f_0(q^2)^2 \times \text{phase space}\,.$$

- It is not just "phase space" × "light leptons".
- But additional piece ∝ additional (pseudo)scalar form factors.
- Assumption: No NP in decays to light leptons.

Anatomy of $R(V)$, $R(P)$ in Scalar Models

Effective Theory and Form Factors

[Fajfer Kamenik Nisandzic 1203.2654, Celis Jung Li Pich 1210.8443]

- Effective theory for charged scalar

$$\mathcal{H}_{\text{eff}} \sim V_{cb}\,(\bar{c}\,(C_L P_L + C_R P_R)\,b)\left(\bar{l} P_L \nu_l\right)\,,$$
$$\Sigma C \equiv C_L + C_R\,, \quad \Delta C \equiv C_L - C_R\,.$$

- Ward identity: Additional hadronic matrix elements

$$\langle V|\,\bar{c}\gamma_5 b\,|B\rangle\,, \quad \langle P|\,\bar{c}\gamma_5 b\,|B\rangle$$

are proportional to SM form factors P_1, f_0, respectively.

Scalar NP modifies factor in front of P_1, f_0 only

[Fajfer Kamenik Nisandzic 1203.2654, Celis Jung Li Pich 1210.8443]

$$\frac{d\Gamma_{\tau}^{D^*}}{dq^2} - \text{P.S.} \times \frac{d\Gamma^{D^*}_{\text{light leptons}}}{dq^2} = \text{P.S.} \times m_\tau^2 P_1^2(q^2) \left| 1 - \Delta C \frac{q^2}{m_\tau (m_b + m_c)} \right|^2 ,$$

$$\frac{d\Gamma_{\tau}^{D}}{dw} - \text{P.S.} \times \frac{d\Gamma^{D}_{\text{light leptons}}}{dq^2} = \text{P.S.} \times m_\tau^2 f_0^2(q^2) \left| 1 + \Sigma C \frac{q^2}{m_\tau (m_b - m_c)} \right|^2 .$$

Different dependence on

$C_L + C_R$ and $C_L - C_R$

advantageous.

True for any $b \to c\tau\nu$ decay mode !

$\Rightarrow$ Relations between $b \to c\tau\nu$ Decay Modes

Connection between Decay Modes $B_q \to V\tau\nu$

[StS Soni, 2007.xxxx]

LHS independent of decay mode.

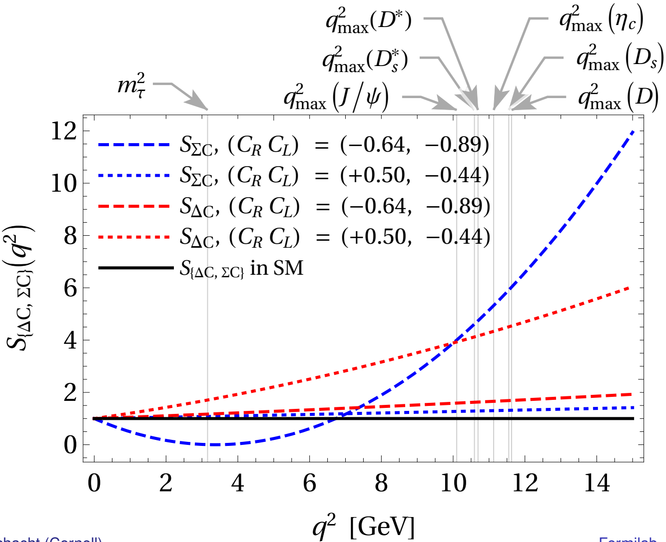
$$S_{\Delta C}(q^2) = \frac{\frac{d\Gamma_\tau^V}{dq^2} - \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma^V_{\text{light leptons}}}{dq^2}}{\text{phase space} \times m_\tau^2 P_1^2(q^2)}$$

Numerator: Experiment. Denominator: Lattice QCD.

$$S_{\Delta C}(q^2) \equiv 1 - 2\mathrm{Re}(\Delta C)\frac{q^2}{m_\tau(m_b + m_c)} + |\Delta C|^2 \left(\frac{q^2}{m_\tau(m_b + m_c)}\right)^2$$

Slope and curvature ∝ scalar NP parameters

$S_{\{\Delta C,\Sigma C\}}(q^2) \sim$ (exp. Data) / (Lattice), for any decay. [StS Soni, 2007.xxxx]



Check of lattice calculations without relying on SM

- Scalar NP cancels in ratios:

$$\frac{d\Gamma_{\tau}^{D^*}/dq^2 - \text{P.S.} \times d\Gamma_{\text{light leptons}}^{D^*}/dq^2}{d\Gamma_{\tau}^{J/\psi}/dq^2 - \text{P.S.} \times d\Gamma_{\text{light leptons}}^{J/\psi}/dq^2} = \frac{P_1^{D^*}(q^2)^2}{P_1^{J/\psi}(q^2)^2} \times \text{phase space}$$

- LHS: Experiment. RHS: Lattice.
- Check ratios directly from data without relying on SM.
- Weaker assumption: at most scalar NP.
- More general NP invalidates the test, but would be seen elsewhere.

Application to $R(V)$ and $R(P)$

Integration of Differential Relations

- Bin-wise relations.
- Special case: integration over complete q^2 range.
- Generates relations between $R(D^*)$, $R(D_s^*)$, $R(J/\psi)$.
- And between $R(D)$, $R(D_s)$, $R(\eta_c)$.

Sum Rules between $R(V_{1,2,3})$ and $\mathcal{B}(B_c \to \tau\nu)$

Scalar Models

[StS Soni 2007.xxxx]

$$\frac{R(V_1) - R^{\rm SM}(V_1)}{R(V_2) - R^{\rm SM}(V_2)} = \frac{\left(\text{function of } P_1^{V_i}\right) \frac{R(V_1)-R^{\rm SM}(V_1)}{R(V_3)-R^{\rm SM}(V_3)}}{\left(\text{function of } P_1^{V_i}\right) + \left(\text{function of } P_1^{V_i}\right) \frac{R(V_1)-R^{\rm SM}(V_1)}{R(V_3)-R^{\rm SM}(V_3)}}$$

- Prefactors: Integrals of pseudoscalar form factors from lattice.
- Similar relation between $R(V_1)$, $R(V_2)$ and $\mathcal{B}(B_c \to \tau\nu)$ and for $R(P_i)$.

Left-Handed Vector Models

[Greljo Isidori Marzocca 1506.01705]

$$\frac{R(D^*)}{R(D^*)^{\rm SM}} = \frac{R(D)}{R(D)^{\rm SM}} = \frac{R(V)}{R(V)^{\rm SM}} = \frac{R(P)}{R(P)^{\rm SM}} = \text{const.}$$

Assumptions for Scalar Sum Rules

1) Only one type of NP, i.e. only scalar NP, not vector or tensor NP.

2) NP only in decays to taus, not to light leptons.

3) Known (pseudo)scalar form factor, as a full function of q^2.

Note that 2) and 3) are not necessary for LH vector sum rule.

Approximation for small 2nd order NP, $|C|^2$

$$\frac{R(V_1) - R^{\rm SM}(V_1)}{R(V_2) - R^{\rm SM}(V_2)} = \left(\text{function of } P_1^{V_i}\right)\,,$$

$$-2\,\mathrm{Re}\,(\Delta C) = \frac{R^{\rm EXP}(V) - R^{\rm SM}(V)}{\left(\text{function of } P_1^{V}\right)} = \frac{1}{r_{B_c}}\left(\frac{\mathcal{B}(B_c \to \tau\nu)}{\mathcal{B}^{\rm SM}(B_c \to \tau\nu)} - 1\right)$$

Analogous for $R(P)$.

Left-Handed Vector Models

[Greljo Isidori Marzocca 1506.01705]

$$\frac{R(D^*)}{R(D^*)^{\rm SM}} = \frac{R(D)}{R(D)^{\rm SM}} = \frac{R(V)}{R(V)^{\rm SM}} = \frac{R(P)}{R(P)^{\rm SM}} = \text{const.}$$

Comparison to Data

Relations between $\mathcal{B}(B_c \to \tau\nu)$, $R(D^*)$ and $R(J/\psi)$ for small scalar NP

Approximate Relations in Scalar Models

$$\mathcal{B}(B_c \to \tau\nu) = \mathcal{N}^{\text{SM}} \left(1 + r_{B_c} \frac{R(D^*) - R^{\text{SM}}(D^*)}{\left(\text{function of } P_1^{D^*}\right)} \right)$$

$$R(J/\psi) = R(J/\psi)^{\text{SM}} + \left(R(D^*) - R^{\text{SM}}(D^*)\right) \frac{\text{function of } P_1^{J/\psi}}{\left(\text{function of } P_1^{D^*}\right)}$$

- Use $B \to D^*\tau\nu$ form factor input from [Gambino Jung StS, 1905.08209].
- And use $B_c \to J/\psi\tau\nu$ form factor input from [Cohen Lamm Lebed 1909.10691].

Consistency Check:
For approximate sum rule, assumed that $|\Delta C|^2$ small.

$$\mathrm{Re}(\Delta C) = -\frac{1}{2}\frac{R(D^*) - R^{\mathrm{SM}}(D^*)}{\left(\text{function of } P_1^{D^*}\right)} = -1.1^{+0.5}_{-0.7}\,.$$

- $|\Delta C|^2$ might be large! Approximation not reliable.
- Need to use relation without approximation.

Relation between $\mathcal{B}(B_c \to \tau\nu)$, $R(D^*)$ and $R(J/\psi)$ for arbitrary scalar NP

$$R(J/\psi) = R(J/\psi)^{\text{SM}} + \frac{\left(\frac{\mathcal{B}(B_c\to\tau\nu)}{\mathcal{N}_{\text{SM}}} - 1\right)\left(\text{function of } P_1^{D^*,J/\psi}\right) + r_{B_c}\left(R(D^*) - R^{\text{SM}(D^*)}\right)\left(\text{function of } P_1^{J/\psi}\right)}{r_{B_c} \times \left(\text{function of } P_1^{D^*}\right)}.$$

- Use conservative bound $0 \leq \mathcal{B}(B_c \to \tau\nu) \leq 0.6$ [Blanke et al 1905.08253]

Scalar model sum rule prediction

$$R(J/\psi) = 0.29 \pm 0.04\,.$$

1.7σ tension with the current measurement $R(J/\psi)^{\text{EXP}} = 0.71 \pm 0.17 \pm 0.18$.

SM Theory

[Murphy Soni 1808.05932, Cohen Lamm Lebed 1807.02730, 1909.10691]

$$R(J/\psi)^{\text{SM}} = 0.25 \pm 0.03\,.$$

Future Data Scenario

Observable	Hypothetical Future Data
$R(J/\psi)^{\mathrm{EXP}}$	0.71 ± 0.05
$R(D^*)^{\mathrm{EXP}}$	0.295 ± 0.006

- 50 ab^{-1}@Belle II: [Belle II Physics Book 1808.10567]
  $R(D^*)$ rel. err. of $(\pm 1.0 \pm 2.0)\%$.
- 50 fb^{-1}@LHCb: [HL/HE-LHC Yellow Report 1812.07638]
  $R(D^*)$ abs. err. of ~ 0.006. $R(J/\psi)$ abs. err. of ~ 0.05.

Updated sum rule prediction

$$R(J/\psi) = 0.29 \pm 0.03\,.$$

$\Rightarrow$ Importance of a future form factor lattice data.

Looking forward to results for $P_1(D^*)$ [FNAL/MILC, 1912.05886 (Lattice 2019)]

Hypothetical data: 7.2σ probing power of scalar models

Only through improved measurement of $R(J/\psi)$ and $R(D^*)$!

Conclusions

- Sum rule tests, probing $b \to c\tau\nu$ for scalar models.
- We need input from Lattice QCD.
- One more piece in the puzzle of the B Anomalies.

BACK-UP

Form Factor Conventions

[Boyd Grinstein Lebed hep-ph/9705252, Bigi Gambino 1606.08030, Bigi Gambino StS 1707.09509]

$$\mathcal{F}_2^{\text{BGL}} = \frac{1 + r_V}{\sqrt{r_V}} P_1 \,, \qquad\qquad f_0 = f_0^{\text{BGL}}/(m_{B_q}^2 - m_P^2) \,,$$

$$\begin{aligned}
\left\langle P(p')\right| \bar{c}\gamma^\mu b \left|\bar{B}_q(p)\right\rangle &= f_+(q^2)(p+p')^\mu + f_-(q^2)(p-p')^\mu \,, \\
\left\langle V(p',\varepsilon)\right| \bar{c}\gamma^\mu b \left|\bar{B}_q(p)\right\rangle &= i g^{\text{BGL}} \varepsilon^{\mu\alpha\beta\gamma} \varepsilon^*_\alpha p'_\beta p_\gamma \,, \\
\left\langle V(p',\varepsilon)\right| \bar{c}\gamma^\mu \gamma_5 b \left|\bar{B}_q(p)\right\rangle &= f^{\text{BGL}} \varepsilon^{*\mu} + (\varepsilon^* \cdot p)\left[a_+^{\text{BGL}}(p+p')^\mu + a_-^{\text{BGL}}(p-p')^\mu\right] \,, \\
f_0(q^2) &= f_+(q^2) + \frac{q^2}{m_{B_q}^2 - m_P^2} f_-(q^2) \,, \\
m_V \mathcal{F}_2^{\text{BGL}}(q^2) &= f^{\text{BGL}}(q^2) + (m_{B_q}^2 - m_V^2) a_+^{\text{BGL}}(q^2) + q^2 a_-^{\text{BGL}}(q^2) \,.
\end{aligned}$$

Decay Rates and Helicity Amplitudes

[Korner Schuler Z.Phys. C46 (1990) 93, Pham PRD47 (1993) 350, Fajfer Kamenik Nisandzic 1203.2654, Celis Jung Li Pich 1210.8443, Bigi Gambino StS 1703.06124]

$$\frac{d\Gamma^V_{\rm EXP}}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2-1}}{48 m_B \pi^3}\left(H^2_{V,00} + H^2_{V,--} + H^2_{V,++}\right),$$

$$\frac{d\Gamma^P_{\rm EXP}}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2-1}}{48 m_B \pi^3} H^2_{P,0}\,.$$

$$\frac{d\Gamma^V_{\tau,\rm EXP}}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2-1}}{48 m_B \pi^3}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \times$$
$$\left(\left(H^2_{V,00} + H^2_{V,--} + H^2_{V,++}\right)\left(1+\frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2} H^2_{V,0t}\right),$$

$$\frac{d\Gamma^P_{\tau,\rm EXP}}{dw} = \frac{|V_{cb}|^2 G_F^2 (m_D^*)^2 q^2 \sqrt{w^2-1}}{48 m_B \pi^3}\left(H^2_{P,0}\left(1+\frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2} H^2_{P,0t}\right).$$

Additional Relations in SM and Scalar Models

$$
\begin{aligned}
0 &= \frac{d\Gamma^{V,T\pm}_{\tau,\mathrm{EXP}}}{dq^2} - \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left(1 + \frac{m_\tau^2}{2q^2}\right) \frac{d\Gamma^{V,T\pm}_{\mathrm{EXP}}}{dq^2} \\
&= \frac{d\Gamma^{\{V,P\}}_{\tau,-,\mathrm{EXP}}}{dq^2} - \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{d\Gamma^{\{V,P\}}_{\mathrm{EXP}}}{dq^2} \,.
\end{aligned}
$$

More general NP violates these relations.

Two Options for Integrating Relations: No. 1

$$\forall\ B_q \to V\tau\nu: \quad \int_{\text{bin}} \frac{d\Gamma_{\tau}^{V,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{V,\text{TH}}/dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{V,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{V,\text{TH}}/dq^2} dq^2$$

$$= 1 - 2\text{Re}(\Delta C) \int_{\text{bin}} \frac{q^2}{m_\tau(m_b + m_c)} dq^2 + |\Delta C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_\tau(m_b + m_c)}\right)^2 dq^2 \,,$$

$$\forall\ B_q \to P\tau\nu: \quad \int_{\text{bin}} \frac{d\Gamma_{\tau}^{P,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{P,\text{TH}}/dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{P,\text{EXP}}/dq^2}{d\Gamma_{\tau,2}^{P,\text{TH}}/dq^2} dq^2$$

$$= 1 + 2\text{Re}(\Sigma C) \int_{\text{bin}} \frac{q^2}{m_\tau(m_b - m_c)} dq^2 + |\Sigma C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_\tau(m_b - m_c)}\right)^2 dq^2 \,.$$

Two Options for Integrating Relations: No. 2

$$\forall\ B_q \to V\tau\nu : \quad \int_{\text{bin}} \frac{d\Gamma_\tau^{V,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{V,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} dq^2$$

$$= -2\text{Re}(\Delta C) \int_{\text{bin}} \frac{q^2}{m_\tau (m_b + m_c)} \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} dq^2 + |\Delta C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_\tau (m_b + m_c)} \right)^2 \frac{d\Gamma_{\tau,2}^{V,\text{TH}}}{dq^2} dq^2 ,$$

$$\forall\ B_q \to P\tau\nu : \quad \int_{\text{bin}} \frac{d\Gamma_\tau^{P,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,1}^{P,\text{EXP}}}{dq^2} dq^2 - \int_{\text{bin}} \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2} dq^2$$

$$= 2\text{Re}(\Sigma C) \int_{\text{bin}} \frac{q^2}{m_\tau (m_b - m_c)} \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2} dq^2 + |\Sigma C|^2 \int_{\text{bin}} \left(\frac{q^2}{m_\tau (m_b - m_c)} \right)^2 \frac{d\Gamma_{\tau,2}^{P,\text{TH}}}{dq^2} dq^2 ,$$

- Analogous eqs. apply to decay rates with fixed D^*- or τ-polarization.
- Use relations for several bins $\Rightarrow$ Solve directly for NP params.

Bin over complete q^2 range

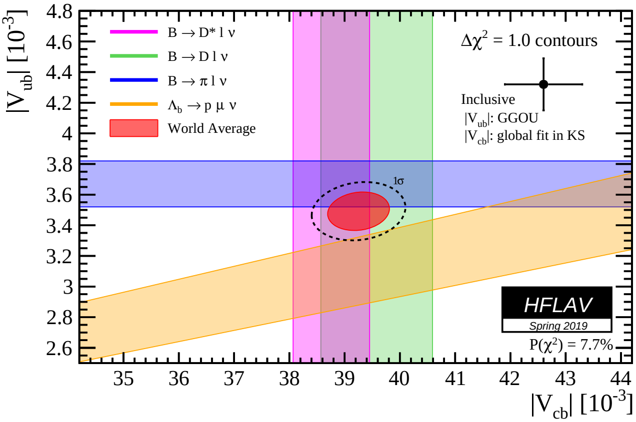
Integrals

$$R^{n}_{\tau,2}(\{V,P\}) \equiv \frac{1}{\Gamma^{\{V,P\}}} \int_{m_\tau^2}^{(m_{B_q}-m_{\{V,P\}})^2} \left(\frac{q^2}{m_\tau(m_b \pm m_c)}\right)^{n} \frac{d\Gamma^{\{V,P\}}_{\tau,2}}{dq^2} dq^2 \,,$$

$$R^{\mathrm{SM}}(\{V,P\}) = R^{\mathrm{TH}}_{\tau,1}(\{V,P\}) + R^{\mathrm{TH}}_{\tau,2}(\{V,P\}) \,,$$

$$\Delta R(\{V,P\}) \equiv R^{\mathrm{EXP}}(\{V,P\}) - R^{\mathrm{SM}}(\{V,P\}) \,.$$

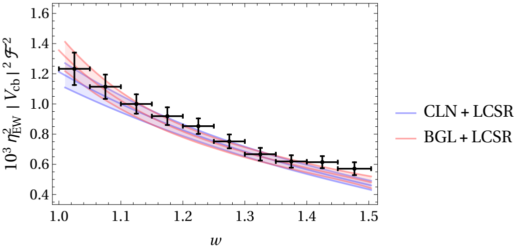
Anomaly II: Exclusive vs. Inclusive V_{cb}, V_{ub} [HFLAV 1909.12524]

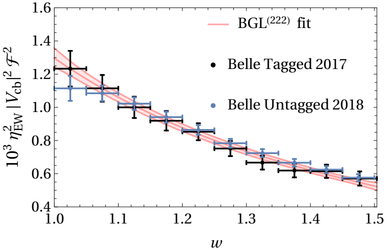


- Recent years:Enter era of precision measurements.
  New results from B-factories, new lattice form factor results.
- Λ_b decays constrain $\frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)} \propto \frac{V_{ub}^2}{V_{cb}^2}$.

Fit to 2017/18 Belle Data + Lattice $A_1(1)$

[FNAL/MILC 1403.0635, HPQCD 1711.11013, FLAG 1902.08191, Belle Tagged 1702.01521, Belle Untagged 1809.03290, Bigi Gambino StS 1703.06124, Gambino Jung StS 1905.08209]





- Depending on parametrization V_{cb} results differed considerably.
- Reappraisal of theoretical errors of parametrizations.

$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}, \quad q^2 = (p_B - p_{D^*})^2 .$$

- Our global $B \to D^* l\nu$ fit gives

$$|V_{cb}| = (39.6^{+1.1}_{-1.0}) \times 10^{-3} .$$

- Differs from inclusive by 1.9σ.
- Very sensitive to slope of form factor, soon available from lattice QCD.

Why is $|V_{cb}|$ so important?

- V_{cb} plays an important role in the Unitarity Triangle.
  ➥We want to overconstrain the triangle as a new physics test.
- V_{cb} goes into the prediction of ε_K via

$$\varepsilon_K \propto x\,|V_{cb}|^4 + \dots\,.$$

- V_{cb} goes into the predictions of flavor changing neutral currents.
- The ratio

$$\left|\frac{V_{ub}}{V_{cb}}\right|$$

directly constrains one side of the Unitarity Triangle.