

ANATOMY OF $b \rightarrow c\tau\nu$ DECAYS

DEBJYOTI BARDHAN
BEN-GURION UNIVERSITY

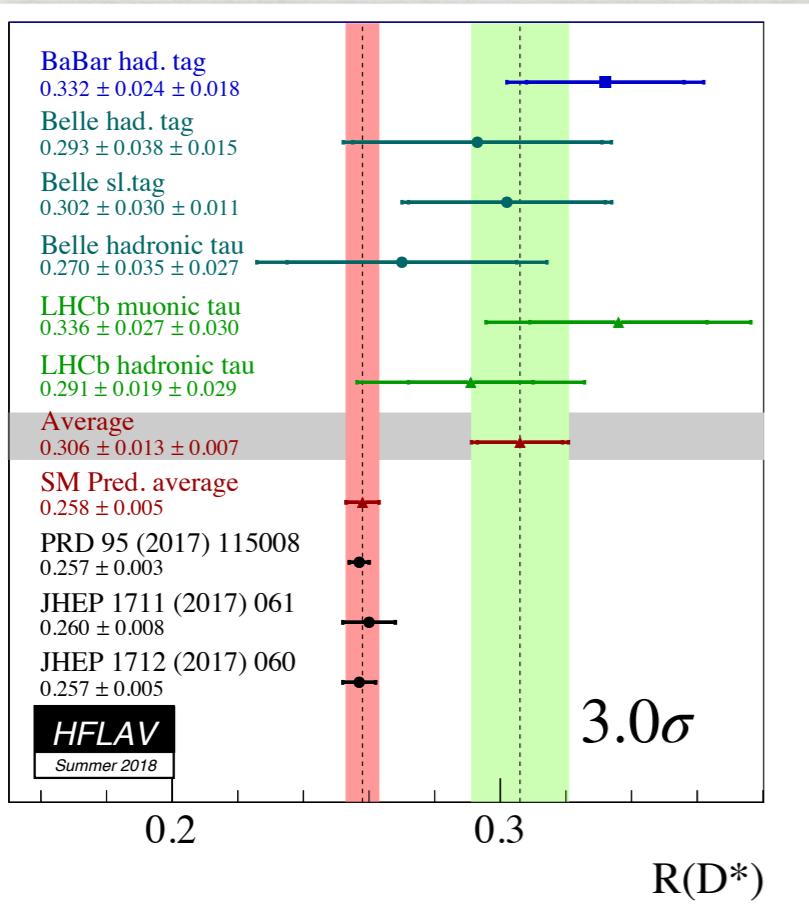
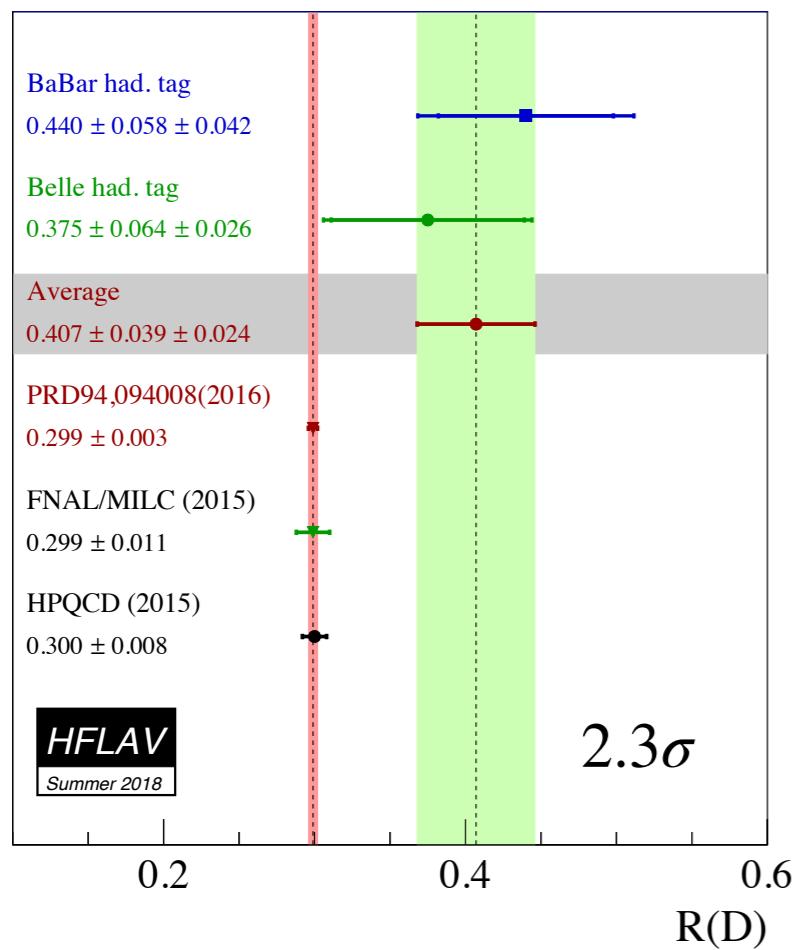
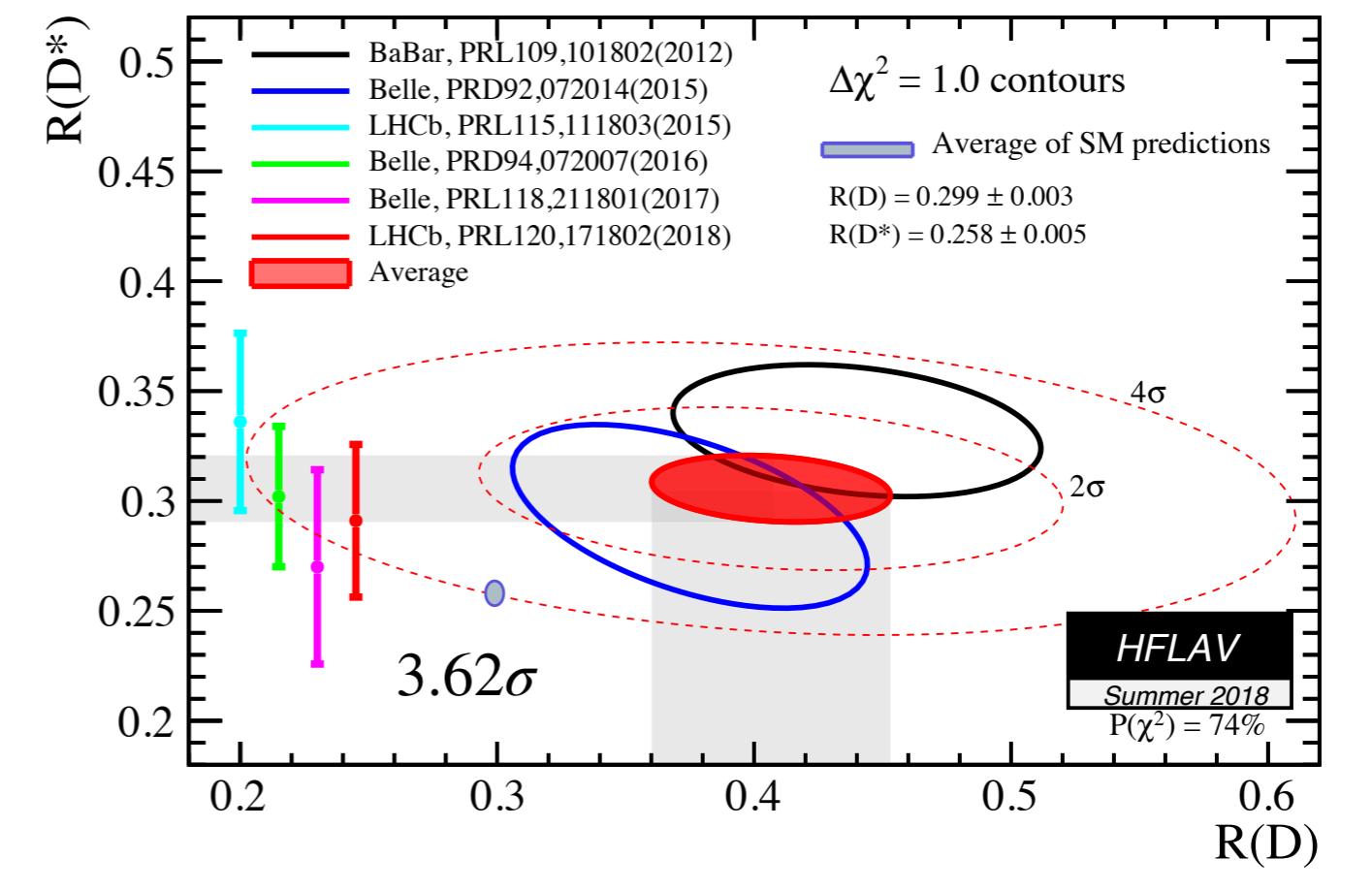
BASED ON: HEP-PH/1805.03209
COLLABORATORS: D. GHOSH, A. AZATOV, E. VENTURINI & F. SGARLATA

SUSY2018

Experimental Status of the Anomalies

- One of the hints of Physics beyond the Standard Model
- Deviation in both the **charged** and neutral current decays of B-meson : suggests lepton non-universality
- This talk - charged sector: combined significance of 3.6σ

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu_\ell)}$$



List of Effective Operators

- In SM, charged current mediated by W-boson via left-left operator
- The Lagrangian is

$$\mathcal{L}_{\text{eff}}^{b \rightarrow c \ell \nu} |_{\text{SM}} = -\sqrt{2} G_F V_{cb} \left([\bar{c} \gamma^\mu (1 - \gamma_5) b] [\bar{\ell} \gamma_\mu P_L \nu] \right)$$

- The suppression for the operator is not $\Lambda^2 = (\sqrt{2} G_F)^{-1}$ but

$$\Lambda_{\text{SM}}^2 = (\sqrt{2} G_F V_{cb})^{-1} \approx (1.2 \text{ TeV})^2$$

- The list of effective operators

Left-chiral neutrinos

Consider this

$$\mathcal{O}_{\text{VL}}^{cb\ell\nu} = [\bar{c} \gamma^\mu b] [\bar{\ell} \gamma_\mu P_L \nu]$$

$$\mathcal{O}_{\text{AL}}^{cb\ell\nu} = [\bar{c} \gamma^\mu \gamma_5 b] [\bar{\ell} \gamma_\mu P_L \nu]$$

$$\mathcal{O}_{\text{SL}}^{cb\ell\nu} = [\bar{c} b] [\bar{\ell} P_L \nu]$$

$$\mathcal{O}_{\text{PL}}^{cb\ell\nu} = [\bar{c} \gamma_5 b] [\bar{\ell} P_L \nu]$$

$$\mathcal{O}_{\text{TL}}^{cb\ell\nu} = [\bar{c} \sigma^{\mu\nu} b] [\bar{\ell} \sigma_{\mu\nu} P_L \nu]$$

Right-chiral neutrinos

Do not consider this

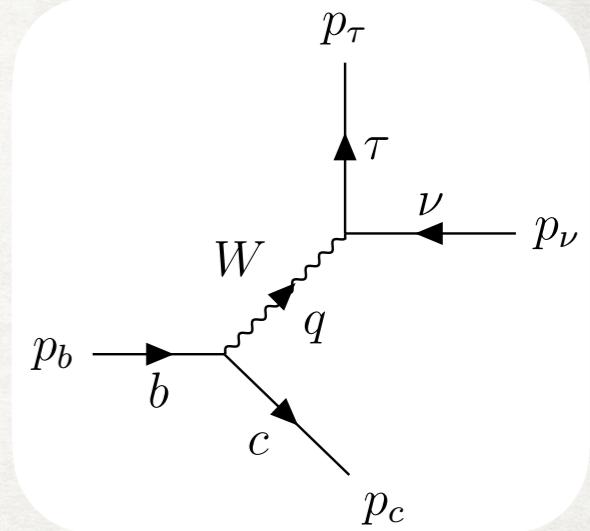
$$\mathcal{O}_{\text{VR}}^{cb\ell\nu} = [\bar{c} \gamma^\mu b] [\bar{\ell} \gamma_\mu P_R \nu]$$

$$\mathcal{O}_{\text{AR}}^{cb\ell\nu} = [\bar{c} \gamma^\mu \gamma_5 b] [\bar{\ell} \gamma_\mu P_R \nu]$$

$$\mathcal{O}_{\text{SR}}^{cb\ell\nu} = [\bar{c} b] [\bar{\ell} P_R^{-1} \nu]$$

$$\mathcal{O}_{\text{PR}}^{cb\ell\nu} = [\bar{c} \gamma_5 b] [\bar{\ell} P_R \nu]$$

$$\mathcal{O}_{\text{TR}}^{cb\ell\nu} = [\bar{c} \sigma^{\mu\nu} b] [\bar{\ell} \sigma_{\mu\nu} P_R \nu]$$



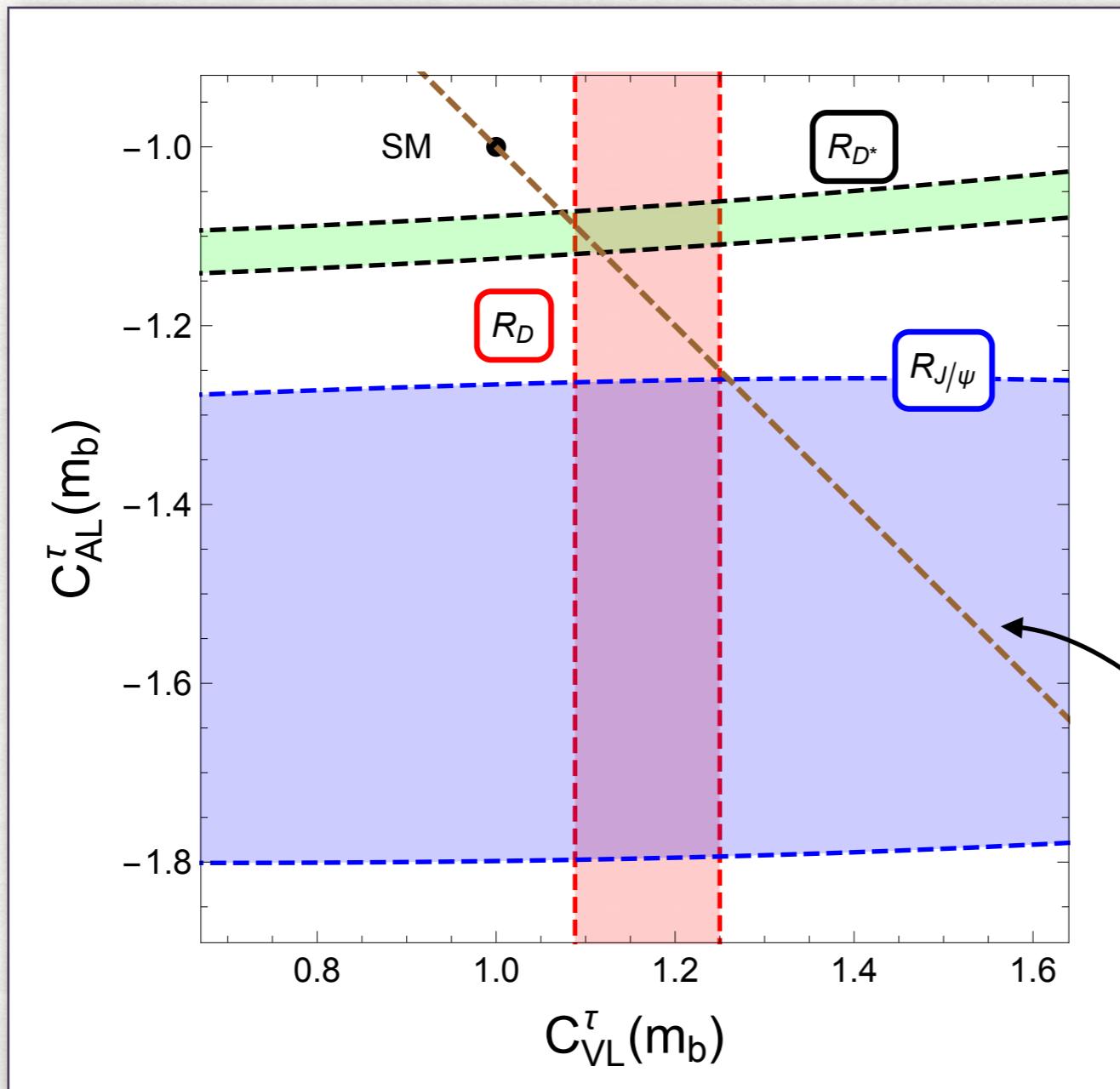
Outline of the Talk

- Model-independent Effective Operator explanations for the anomaly
 - Vector
 - Scalar
 - Tensor+Scalar
- Correlations between Neutral and Charged Current Processes
 - Modification of vertices
 - Four-fermion operator
- $\Delta F = 2$ Processes, as counterparts to the $\Delta F = 1$ processes
- Summary

ALL EXPLANATIONS AND
CONSTRAINTS AT 1 SIGMA

The Vector Explanation

- One can attempt an explanation using one operator at a time, or a combination
- Try out a vector combination



$$\mathcal{O}_{VL}^{cb\ell\nu} = [\bar{c} \gamma^\mu b][\bar{\ell} \gamma_\mu P_L \nu]$$

$$\mathcal{O}_{AL}^{cb\ell\nu} = [\bar{c} \gamma^\mu \gamma_5 b][\bar{\ell} \gamma_\mu P_L \nu]$$

$$\mathcal{O}_{SL}^{cb\ell\nu} = [\bar{c} b][\bar{\ell} P_L \nu]$$

$$\mathcal{O}_{PL}^{cb\ell\nu} = [\bar{c} \gamma_5 b][\bar{\ell} P_L \nu]$$

$$\mathcal{O}_{TL}^{cb\ell\nu} = [\bar{c} \sigma^{\mu\nu} b][\bar{\ell} \sigma_{\mu\nu} P_L \nu]$$

$R_D : C_{VL}^\tau$ only
 $R_{D^*} : C_{VL}^\tau \& C_{AL}^\tau$

$$C_{VL}^\tau = - C_{AL}^\tau = 1.1$$

$$\Delta C_{VL,AL} = 10\%$$

$$C_{VL}^\tau = - C_{AL}^\tau$$

SU(2) \times U(1) gauge invariance

The Scalar Explanation

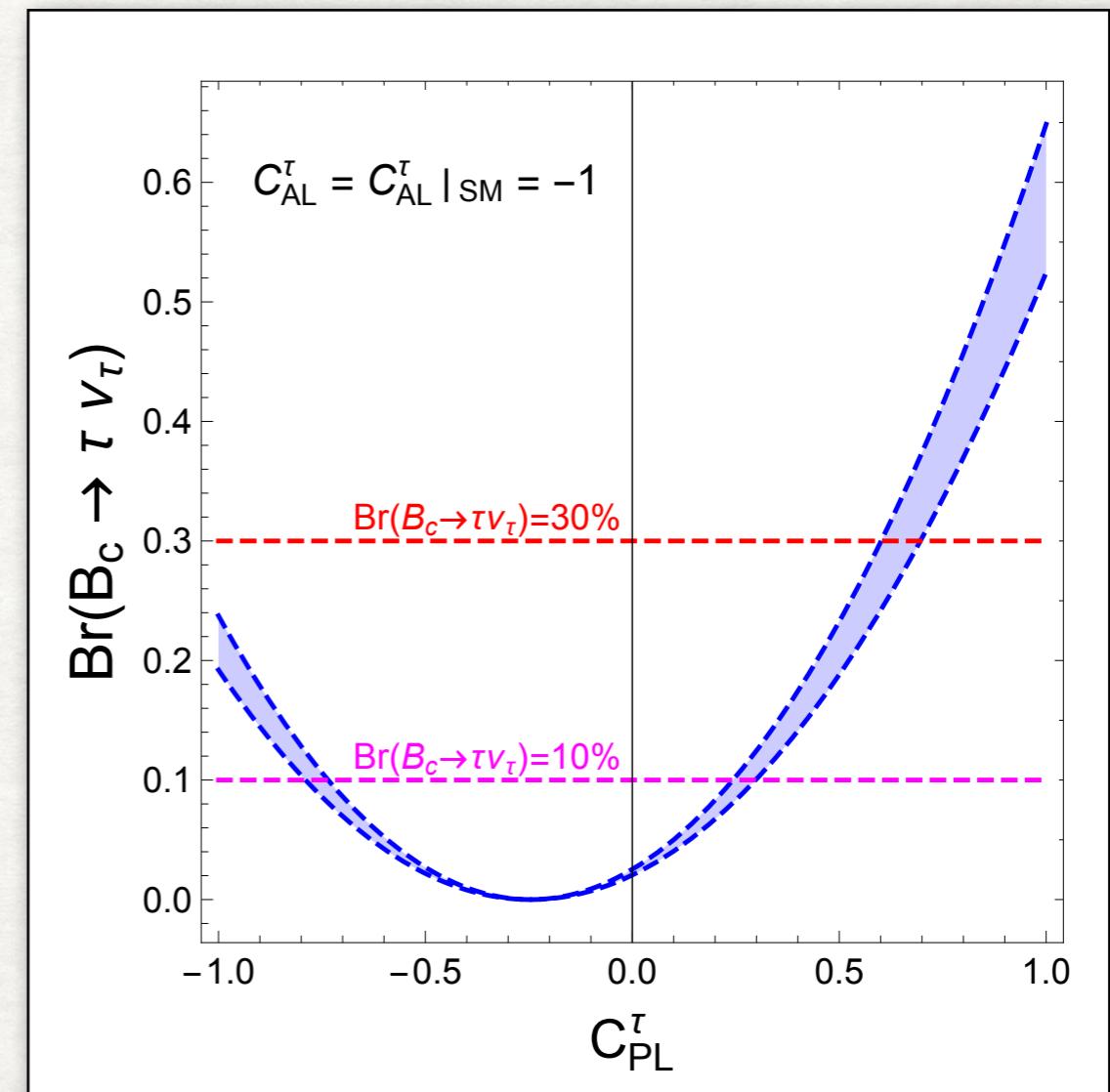
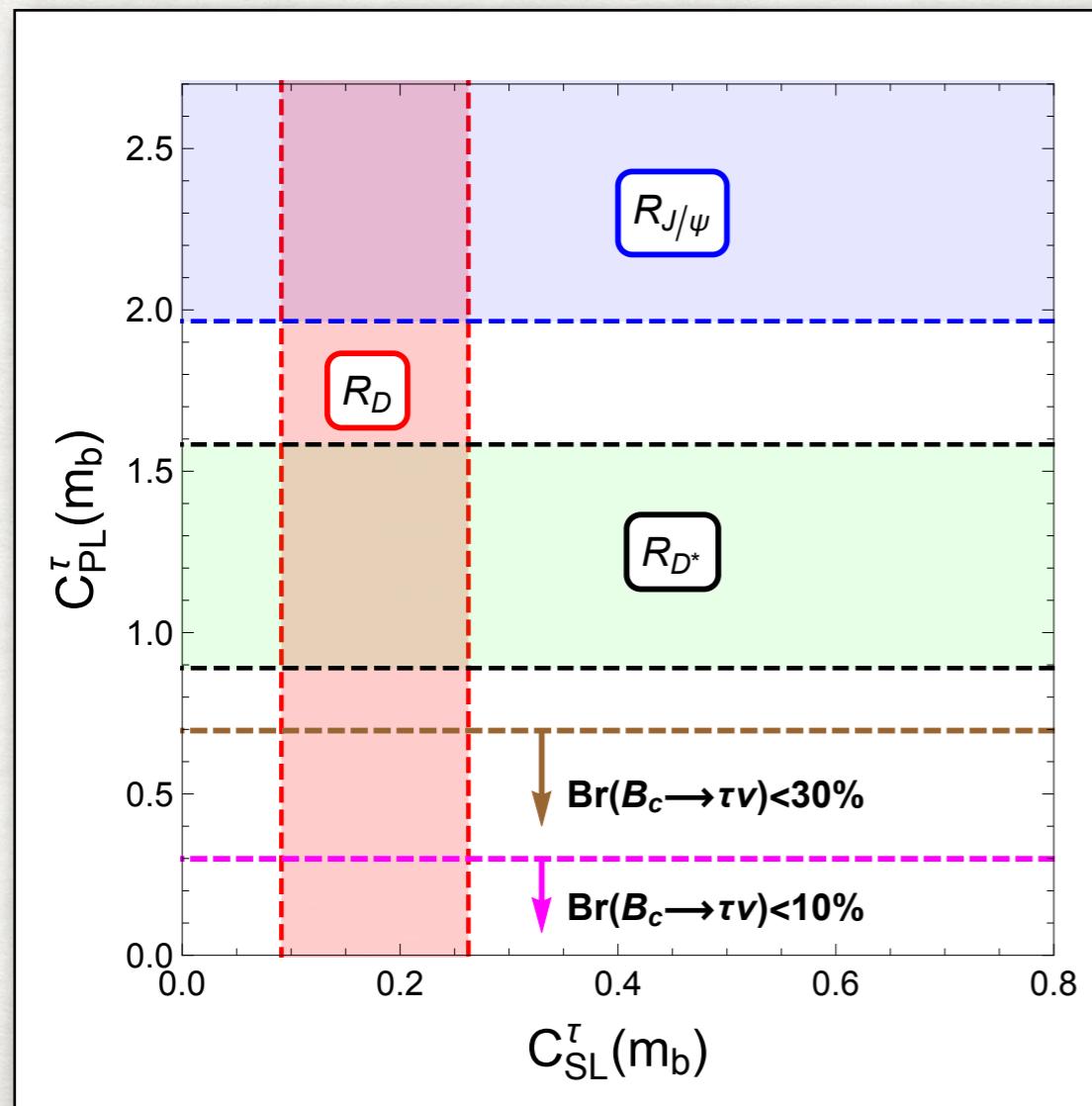
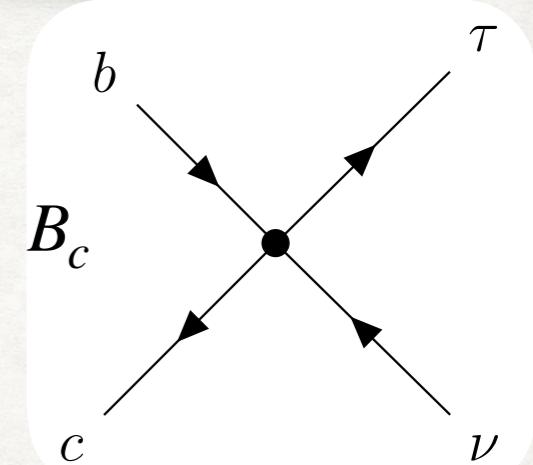
- Operator contributing to $B \rightarrow D^* \tau \nu$ also contributes to $B_c \rightarrow \tau \nu$
- Strong constraints coming from B_c lifetime

30% : R. Alonso, B. Grinstein and J. Martin Camalich
Phys. Rev. Lett. 118 (2017) 081802

10% : A. G. Akeroyd and C.-H. Chen
Phys. Rev. D 96 (2017) 075011

$$R_D : C_{SL}^\tau \text{ only}$$

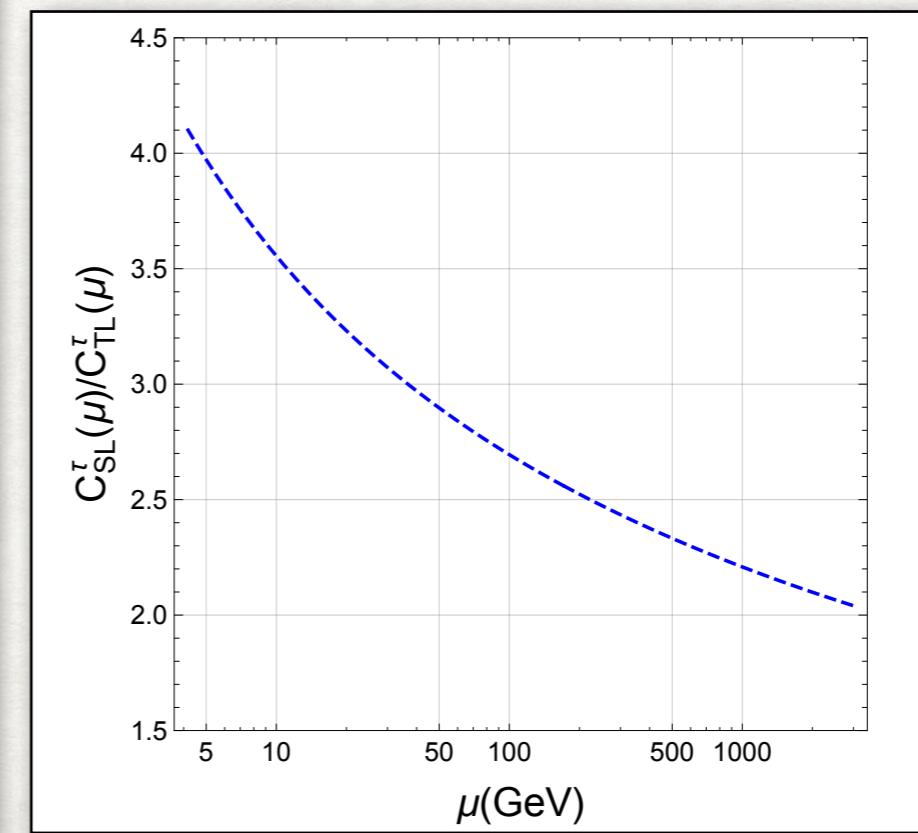
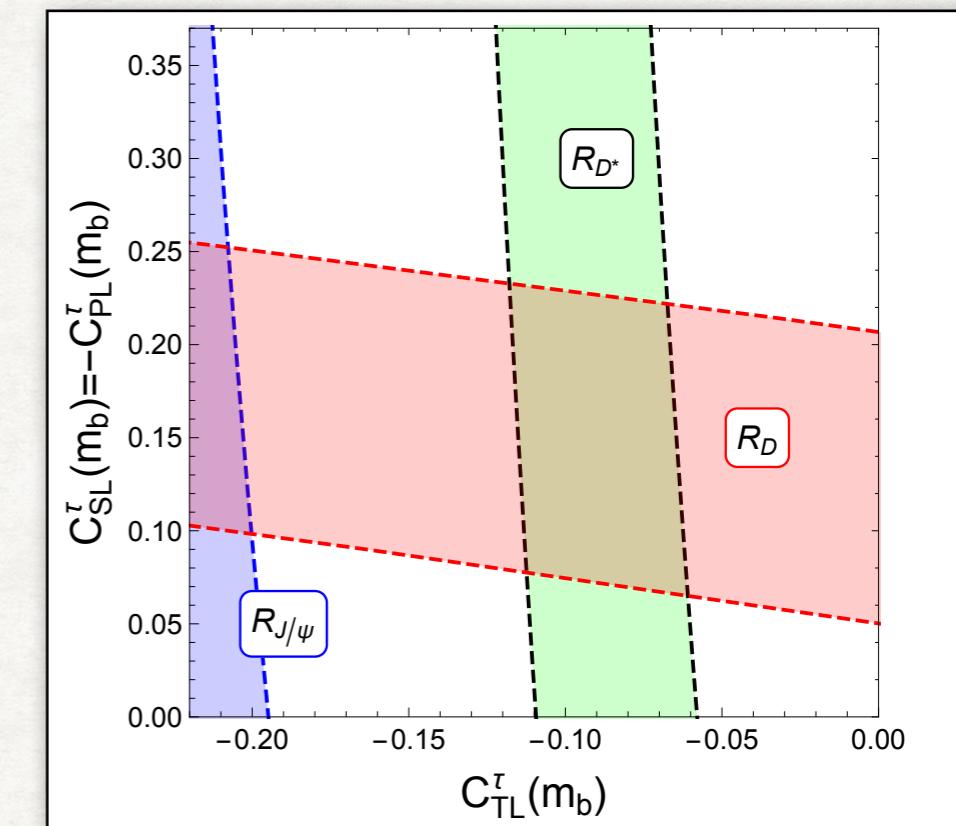
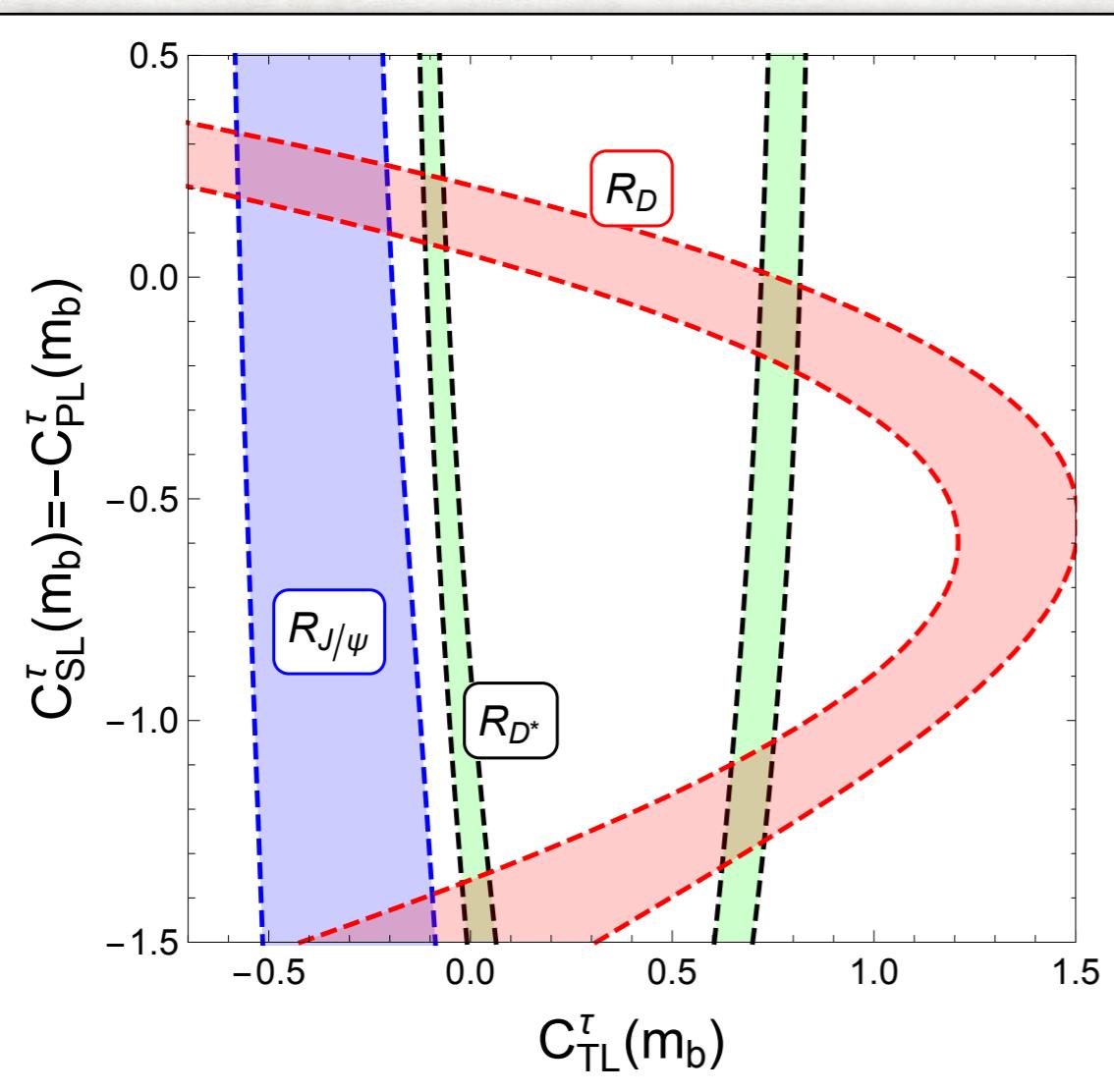
$$R_{D^*} : C_{PL}^\tau \text{ only}$$



Tensor and Scalar Explanation

- Tensor and scalar operators taken together
- Evades the $B_c \rightarrow \tau\nu$ branching ratio bound
- Running important - leptoquark operators generated at high scale

$$(\bar{c}P_L\nu)(\bar{\tau}P_L b) = -\frac{1}{8} [2(\mathcal{O}_{SL}^\tau - \mathcal{O}_{PL}^\tau) + \mathcal{O}_{TL}^\tau]$$



Ratio = 2 at high scale

From $SU(2) \times U(1)$ symmetric operators

- Six-dimensional effective operators with $SU(2) \times U(1)$ symmetry

$$\mathcal{L}^{\text{dim6}} = -\frac{1}{\Lambda^2} \sum_{p' r' s' t'} \left\{ [C_{lq}^{(3)}]_{p' r' s' t'}' \boxed{(\bar{l}'_{p'} \gamma_\mu \sigma^I l'_{r'}) (\bar{q}'_{s'} \gamma^\mu \sigma^I q'_{t'})} + \text{h.c.} \right.$$

$$+ [C_{ledq}]_{p' r' s' t'}' \left(\bar{l}'_{p'}^j e'_{r'} \right) \left(\bar{d}'_{s'} q'_{t'}^j \right) + \text{h.c.}$$

$$+ [C_{lequ}^{(1)}]_{p' r' s' t'}' \left(\bar{l}'_{p'}^j e'_{r'} \right) \epsilon_{jk} \left(\bar{q}'_{s'}^k u'_{t'} \right) + \text{h.c.}$$

$$+ [C_{lequ}^{(3)}]_{p' r' s' t'}' \left(\bar{l}'_{p'}^j \sigma_{\mu\nu} e'_{r'} \right) \epsilon_{jk} \left(\bar{q}'_{s'}^k \sigma^{\mu\nu} u'_{t'} \right) + \text{h.c.}$$

4-fermion
operators

$$+ [C_{\phi l}^{(3)}]_{p' r'}' \boxed{(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi) (\bar{l}'_{p'} \sigma^I \gamma^\mu l'_{r'})} + \text{h.c.}$$

Charged & neutral
current vertex - leptonic

$$+ [C_{\phi q}^{(3)}]_{p' r'}' \left(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi \right) \left(\bar{q}'_{p'} \sigma^I \gamma^\mu q'_{r'} \right) + \text{h.c.}$$

Charged & neutral
current vertex - quark

$$+ [C_{\phi ud}]_{p' r'}' \left(\phi^j \epsilon_{jk} i (D_\mu \phi)^k \right) \left(\bar{u}'_{p'} \gamma^\mu d'_{r'} \right) + \text{h.c.} \right\}$$

Constraints from correlated processes

- Using a $SU(2)_L \times U(1)_Y$ symmetric operators, there are correlations between charged and neutral currents, or from such vertices

CHARGED & NEUTRAL
CURRENT VERTEX
MODIFICATION

$$[C_{\phi l}^{(3)}]_{p' r'}' \left(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi \right) (\bar{l}'_{p'} \sigma^I \gamma^\mu l'_{r'})$$

- Modify the charged current vertex to explain the anomalies
- W-vertex and Z-vertex are correlated
- Constraints from $Z\nu\nu$ and $W\tau\nu$

FOUR-FERMION
VERTEX

$$[C_{lq}^{(3)}]_{p' r' s' t'}' \left(\bar{l}'_{p'} \gamma_\mu \sigma^I l'_{r'} \right) \left(\bar{q}'_{s'} \gamma^\mu \sigma^I q'_{t'} \right)$$

- Contribution to the charged 4-fermion vertex
- Processes like $b \rightarrow c\tau\nu$ and $b \rightarrow s\nu\nu$ correlated

Scalar - Fermion Vertex

$$\begin{aligned}
 (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi) (\bar{l}'_{p'} \sigma^I \gamma^\mu l'_{r'}) &= \left[-\frac{1}{2} \frac{g_2}{\cos\theta_W} Z_\mu (\bar{\nu}'_{p'} \gamma^\mu P_L \nu'_{r'}) + \frac{1}{2} \frac{g_2}{\cos\theta_W} Z_\mu (\bar{e}'_{p'} \gamma^\mu P_L e'_{r'}) \right. \\
 &\quad \left. - \frac{g_2}{\sqrt{2}} W_\mu^+ (\bar{\nu}'_{p'} \gamma^\mu P_L e'_{r'}) - \frac{g_2}{\sqrt{2}} W_\mu^- (\bar{e}'_{p'} \gamma^\mu P_L \nu'_{r'}) \right] (v^2 + 2vh + h^2) \\
 &= [C_{\phi l}^{(3)}]' [\{Z \bar{\nu} \nu + Z \bar{e} e\}_{V-A} + \{W \bar{e} \nu + W \bar{\nu} e\}_{V-A}]
 \end{aligned}$$

MODIFICATION OF CHARGED CURRENT VERTEX

Lepton non-universality at the vertices may explain $R_{D^{(*)}}$

$$\mathcal{L}_{W\tau\nu} = -\frac{g_2}{\sqrt{2}} (1 + \Delta g_L^\tau) \left(W_\mu^- \bar{\tau} \gamma^\mu P_L \nu_\tau + W_\mu^+ \bar{\nu}_\tau \gamma^\mu P_L \tau \right)$$

$$\Delta g_L^\tau = \frac{1}{2} \frac{v^2}{\Lambda^2} \left[\left([\tilde{C}_{\phi l}^{(3)e\nu}] \right) V_{\text{PMNS}} \right]_{33}$$

BOUNDS FROM LEP

$$\frac{\text{Br}(W^+ \rightarrow \tau^+ \nu)}{[\text{Br}(W^+ \rightarrow \mu^+ \nu) + \text{Br}(W^+ \rightarrow e^+ \nu)]/2} = 1.077 \pm 0.026 \quad \Rightarrow \text{10 \% deviation}$$

$$\Rightarrow \Delta C_{\text{VL}}^\tau = -\Delta C_{\text{AL}}^\tau < 0.05$$

Too small to explain the observed anomaly in $R_{D^{(*)}}$

Scalar - Fermion Vertex

MODIFICATION OF NEUTRAL CURRENT VERTEX

$$\mathcal{L}_{Z\nu\nu} = -\frac{g_2}{\cos \theta_W} (1 + \Delta g_L^\nu) Z_\mu \bar{\nu}_\tau \gamma^\mu P_L \nu_\tau$$

$$\Delta g_L^\nu = -\frac{1}{2} \frac{v^2}{\Lambda^2} \left[V_{\text{PMNS}} [\tilde{C}_{\phi l}^{(3)e\nu}] V_{\text{PMNS}}^\dagger \right]_{33}$$

BOUNDS FROM LEP

$$|\Delta g_L^\nu| \lesssim 1.2 \times 10^{-3}$$

$$|\Delta C_{\text{VL}}^\tau| < 0.022$$

$$\mathcal{L}_{Z\tau\tau} = -\frac{g_2}{\cos \theta_W} Z_\mu \left((g_L^\tau + \Delta g_L^\tau) \bar{\tau} \gamma^\mu P_L \tau + (g_R^\tau + \Delta g_R^\tau) \bar{\tau} \gamma^\mu P_R \tau \right)$$

$$\Delta g_L^\tau = \frac{1}{8} \frac{g_2}{\cos \theta_W} \frac{v^2}{\Lambda^2} \left[\left([\tilde{C}_{\phi l}^{(3)e\nu}] \right) V_{\text{PMNS}} \right]_{33}$$

$$\Delta g_R^\tau = 0.$$

BOUNDS FROM LEP

$$|\Delta g_L^\tau| \lesssim 6 \times 10^{-4}$$

$$|\Delta C_{\text{VL}}^\tau| < 0.001$$

Way too small to explain the anomaly

4-Fermion Operator

- The SU(2)xU(1) operator can be decomposed

$$\begin{aligned}
 (\bar{l}'_{p'} \gamma_\mu \sigma^I l'_{r'}) (\bar{q}'_{s'} \gamma^\mu \sigma^I q'_{t'}) &= (\bar{\nu}'_{p'} \gamma^\mu P_L \nu'_{r'}) (\bar{u}'_{s'} \gamma_\mu P_L u'_{t'}) + (\bar{e}'_{p'} \gamma^\mu P_L e'_{r'}) (\bar{d}'_{s'} \gamma_\mu P_L d'_{t'}) \\
 &\quad - (\bar{e}'_{p'} \gamma^\mu P_L e'_{r'}) (\bar{u}'_{s'} \gamma_\mu P_L u'_{t'}) - (\bar{\nu}'_{p'} \gamma^\mu P_L \nu'_{r'}) (\bar{d}'_{s'} \gamma_\mu P_L d'_{t'}) \\
 &\quad + 2 (\bar{\nu}'_{p'} \gamma^\mu P_L e'_{r'}) (\bar{d}'_{s'} \gamma_\mu P_L u'_{t'}) + 2 (\bar{e}'_{p'} \gamma^\mu P_L \nu'_{r'}) (\bar{u}'_{s'} \gamma_\mu P_L d'_{t'}) \\
 &= [\{\bar{u}u\bar{\nu}\nu + \bar{d}d\bar{e}e + \bar{u}u\bar{e}e + \bar{d}d\bar{\nu}\nu\}_{V-A} + \{2\bar{d}u\bar{\nu}e + 2\bar{u}d\bar{e}\nu\}_{V-A}]
 \end{aligned}$$

Neutral current Charged current

- Try to constraint possible explanations of CC anomalies by NC measurements

CONTRIBUTION TO $(\bar{\tau} \gamma_\mu P_L \nu_\tau)(\bar{c} \gamma_\mu P_L b)$

$$\approx ([C_{lq}^{(3)}]_{3313}' V_{cd} + [C_{lq}^{(3)}]_{3323}' V_{cs} + [C_{lq}^{(3)}]_{3333}' V_{cb})(\bar{\tau} \gamma^\mu P_L \nu_\tau)(\bar{c} \gamma_\mu P_L b)$$

- To explain the anomalies, prefactor = 0.16

$$\Rightarrow ([C_{lq}^{(3)}]_{3313}' V_{cd} + [C_{lq}^{(3)}]_{3323}' V_{cs} + [C_{lq}^{(3)}]_{3333}' V_{cb}) \geq 0.03 \left(\frac{\Lambda_{\text{SM}}^2}{\text{TeV}^2} \right)$$

$\Lambda_{\text{SM}} = 1.2 \text{ TeV}$

- Each term is constrained by a neutral current process

4-Fermion Operator : Constraints

► CONSTRAINING $[C_{lq}^{(3)}]_{3313}$

BOUNDS FROM $(\bar{\nu}\gamma_\mu P_L \nu)(\bar{d}\gamma_\mu P_L b)$

$B^0 \rightarrow \pi^0 \bar{\nu}\nu$

$$-0.018 \left(\frac{\Lambda^2}{\text{TeV}^2} \right) \lesssim [C_{lq}^{(3)}]_{3313}' \lesssim 0.023 \left(\frac{\Lambda^2}{\text{TeV}^2} \right)$$

BOUNDS FROM $(\bar{\tau}\gamma_\mu P_L \nu_\tau)(\bar{b}\gamma_\mu P_L u)$

$B_u \rightarrow \bar{\tau}\nu_\tau$

$$-0.15 \left(\frac{\Lambda^2}{\text{TeV}^2} \right) \lesssim [C_{lq}^{(3)}]_{3313}' \lesssim 0.025 \left(\frac{\Lambda^2}{\text{TeV}^2} \right)$$

► CONSTRAINING $[C_{lq}^{(3)}]_{3323}$

BOUNDS FROM $(\bar{\nu}\gamma_\mu P_L \nu)(\bar{s}\gamma_\mu P_L b)$

$B^0 \rightarrow K^{*0} \bar{\nu}\nu$

$$-0.005 \left(\frac{\Lambda^2}{\text{TeV}^2} \right) \lesssim [C_{lq}^{(3)}]_{3323}' \leq 0.025 \left(\frac{\Lambda^2}{\text{TeV}^2} \right)$$

Thus, we need

$$([C_{lq}^{(3)}]_{3333}') V_{cb} \gtrsim 0.03 \left(\frac{\Lambda^2}{\text{TeV}^2} \right)$$

4-Fermion Operator : Constraints

CONTRIBUTION TO $(\bar{t}\gamma_\mu P_L t)(\bar{b}\gamma_\mu P_L b)$

$$[\tilde{C}_{lq}^{(3)eedd}]_{3333} + \left([\tilde{C}_{lq}^{(3)eedd}]_{3333} \right)^* = [C_{lq}^{(3)}]_{3333}' + \left([C_{lq}^{(3)}]_{3333}' \right)^*$$

$$\left| [C_{lq}^{(3)}]_{3333}' + ([C_{lq}^{(3)}]_{3333}')^* \right| < 2.6 \left(\frac{\Lambda^2}{\text{TeV}^2} \right)$$

Weak bound

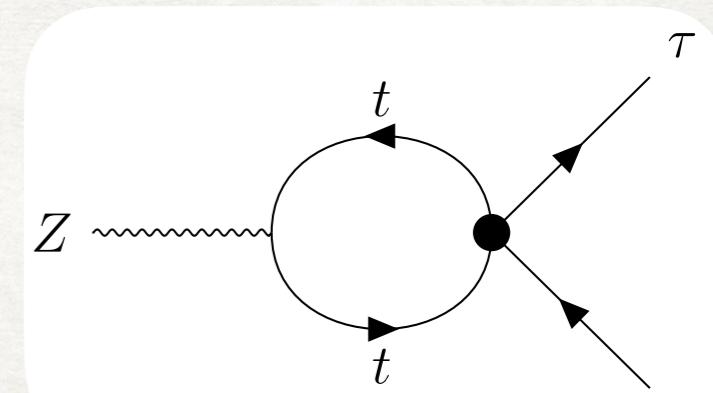
Also CONTRIBUTION TO $(\bar{t}\gamma_\mu P_L t)(\bar{t}\gamma_\mu P_L t)$

$$[\tilde{C}_{lq}^{(3)eeuu}]_{3333} \approx [C_{lq}^{(3)}]_{3333}' |V_{tb}|^2$$

The top quark loop generates a NC vertex and Δg_L^τ

But the $Z\tau\tau$ vertex is severely constrained by LEP data

$$\left| [C_{lq}^{(3)}]_{3333}' \right| \lesssim \frac{0.017}{V_{cb}} \left(\frac{\Lambda}{\text{TeV}} \right)^2 \frac{1}{1 + 0.6 \log \frac{\Lambda}{\text{TeV}}}$$



However, from the earlier analysis on charged currents:

$$([C_{lq}^{(3)}]_{3333}') V_{cb} \gtrsim 0.03 \left(\frac{\Lambda^2}{\text{TeV}^2} \right)$$

★ Impossible to explain the anomaly with just this operator

Need additional ops to cancel contribution to NC processes

$$(\bar{l}'_p \gamma_\mu l'_r) (\bar{q}'_s \gamma^\mu q'_t)$$

$\Delta F = 2$ Processes

Assume a model to relate $\Delta F = 1$ and $\Delta F = 2$ process

Relate $2L2Q$ to $4Q$ operators

$$(\bar{\tau}\gamma^\mu P_L \nu_\tau)(\bar{c}\gamma_\mu P_L b) \leftrightarrow (\bar{s}\gamma^\mu P_L b)(\bar{s}\gamma_\mu P_L b)$$

Assumption: Either a SU(2) triplet or a leptoquark operator



Coupling of $(\bar{\tau}\gamma^\mu P_L \nu_\tau)(\bar{c}\gamma_\mu P_L b) \approx \frac{1}{\Lambda^2} V_{cs} [C_{lq}^{(3)}]_{3323}'$

Separate out the leptonic and quark parts

$$[C_{lq}^{(3)}]_{3323}' = \frac{[C_{lq;l}]_{33}'}{\Lambda} + \frac{[C_{lq;q}]_{23}'}{\Lambda}$$

Lepton Quark

Consider the operator giving $\bar{B}_s - B_s$ oscillations $(\bar{s}\gamma^\mu P_L b)(\bar{s}\gamma_\mu P_L b) : \left(\frac{[C_{lq;q}]_{23}'}{\Lambda} \right)^2$

$\Delta F = 2$ Processes

BOUNDS FROM OSCILLATION DATA

$$\frac{1}{2} \left(\frac{[C_{lq;q}^{(3)}]_{23}'}{\Lambda} \right)^2 < 5.6 \times 10^{-11} \text{ GeV}^{-2} \implies \left(\frac{[C_{lq;q}^{(3)}]_{23}'}{\Lambda} \right) < 0.011 \text{ TeV}^{-1}$$

For charged currents

$$\Delta(C_{VL}^\tau - C_{AL}^\tau) < 0.008 [C_{lq;l}^{(3)}]_{33}' \left(\frac{\text{TeV}}{\Lambda} \right)$$

$$[C_{lq}^{(3)}]_{3323}' = \frac{[C_{lq;l}^{(3)}]_{33}'}{\Lambda} \frac{[C_{lq;q}^{(3)}]_{23}'}{\Lambda}$$

Required

$$\Delta(C_{VL}^\tau - C_{AL}^\tau) \approx 0.20$$

Difficult with tree-level exchange - problem for SU(2) triplet (W')

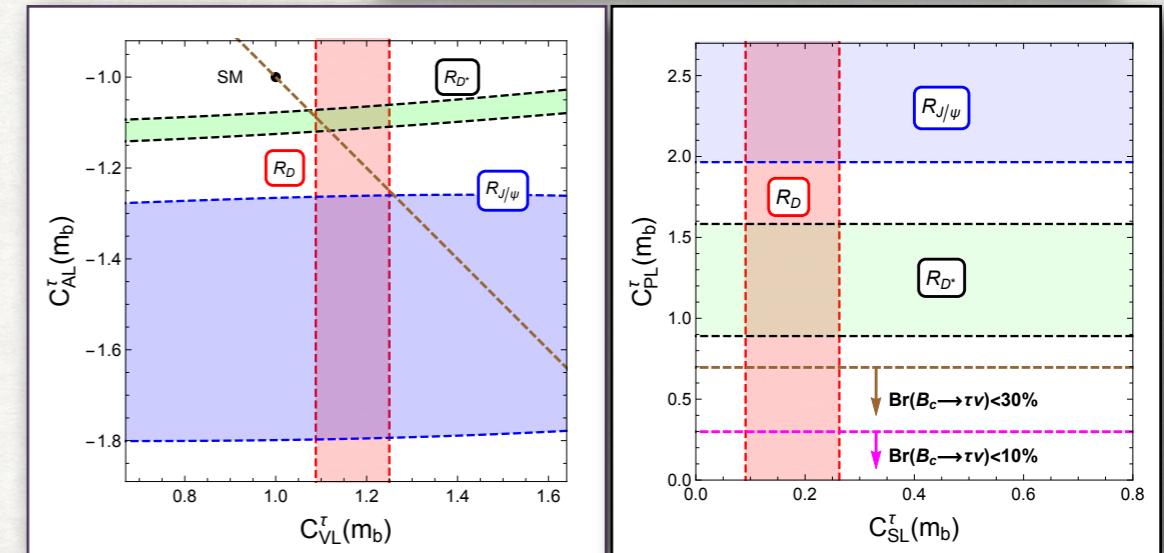
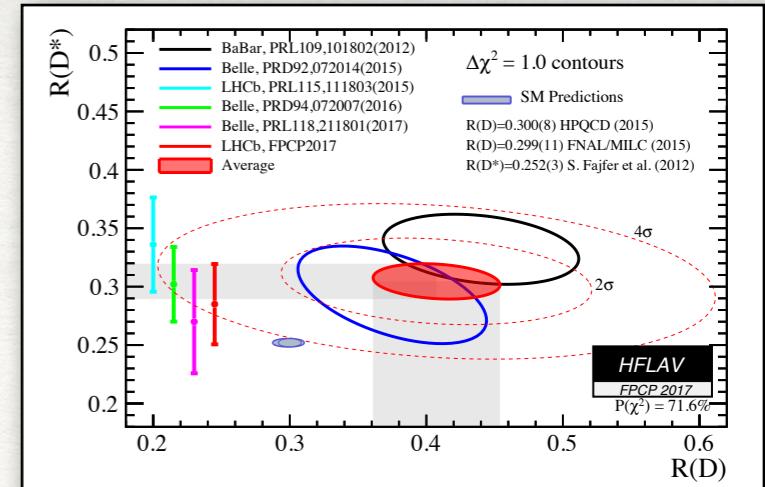
Bounds evaded with loop level LQ exchange

Summary

Persistent anomaly in the B-meson sector

Attempted a model-independent explanation using the various effective operators

- Vector
- Scalar
- Tensor+Scalar



SU(2) x U(1) symmetry creates correlation between charged and neutral current processes

- Modifying the CC and NC vertex
- Four-fermion operator
- Difficult to explain with just one operator

Constraints from oscillation data, for $\Delta F = 2$ processes

THANK YOU!

BACKUP SLIDES

Word on Uncertainties

For $B \rightarrow D$ decay

$\mathcal{B}(B \rightarrow D\tau\nu_\tau)$	$0.633 \pm 0.014\%$	2.2%
$\mathcal{B}(B \rightarrow Dl\nu_l)$	$2.11 \pm 0.11\%$	5%
R_D	0.300 ± 0.011	3.7%

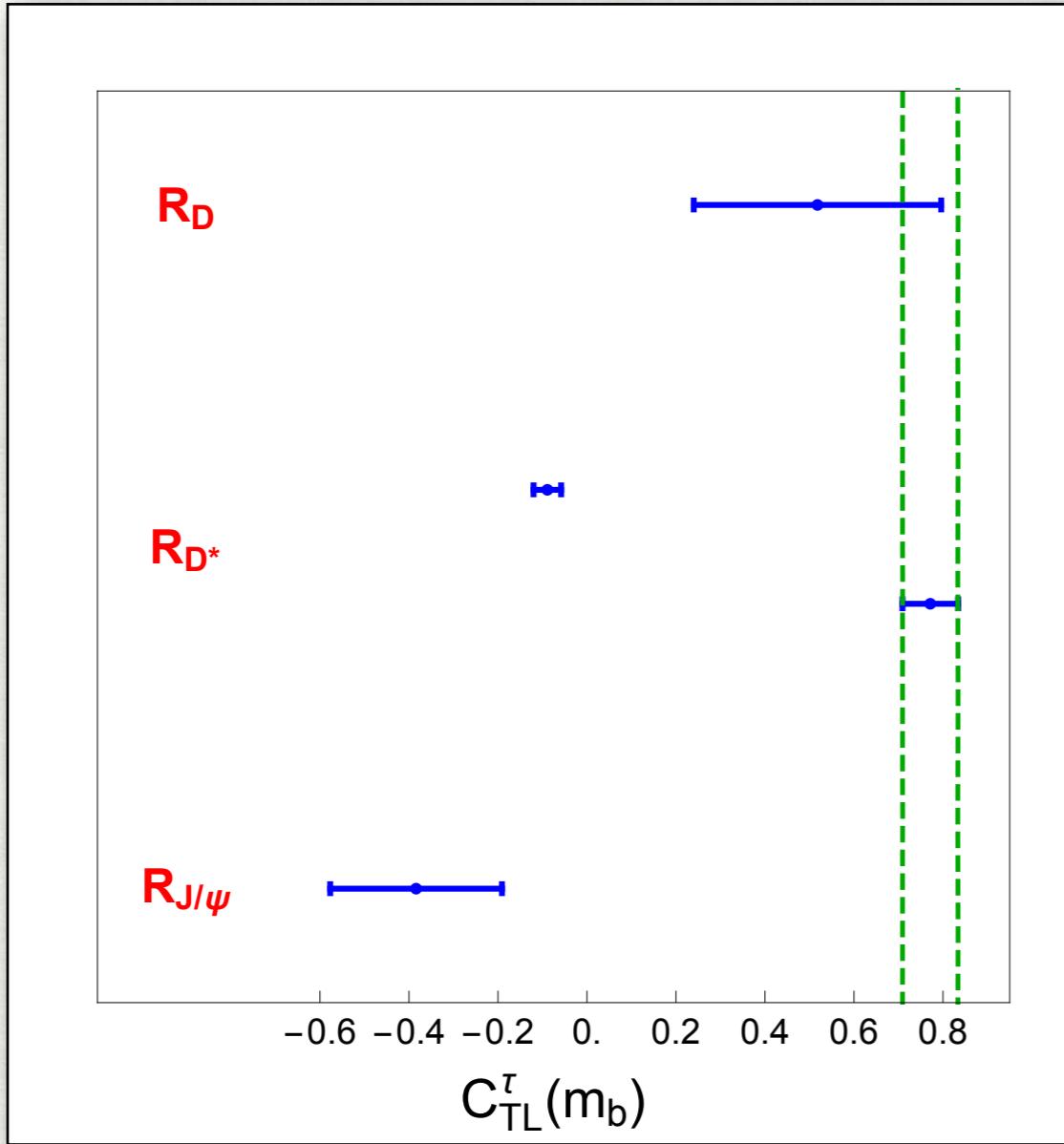
$$\begin{aligned}\text{Br}(B \rightarrow D\tau\nu_\tau) &= [0.370\%]_{F_0^2} + [0.263\%]_{F_+^2} = [0.633\%]_{\text{Total}} \\ \text{Br}(B \rightarrow Dl\nu_l) &= [0.016\%]_{F_0^2} + [2.095\%]_{F_+^2} = [2.111\%]_{\text{Total}}\end{aligned}$$

For $B \rightarrow D^*$ decay

$\mathcal{B}(B \rightarrow D^*\tau\nu_\tau)$	$1.28 \pm 0.09\%$	7%
$\mathcal{B}(B \rightarrow D^*l\nu_l)$	$5.03 \pm 0.43\%$	8.5%
R_{D^*}	0.254 ± 0.004	1.5%

$$\begin{aligned}\text{Br}(B \rightarrow D^*\tau\nu_\tau) &= [0.072\%]_{V^2} + [0.117\%]_{A_0^2} + [1.31\%]_{\mathbf{A}_1^2} + [0.025\%]_{A_2^2} + [-0.242\%]_{A_1 A_2} \\ &= [1.28\%]_{\text{Total}} \\ \text{Br}(B \rightarrow D^*\ell\nu_\ell) &= [0.350\%]_{V^2} + [0.012\%]_{A_0^2} + [7.16\%]_{\mathbf{A}_1^2} + [0.472\%]_{A_2^2} + [-2.96\%]_{A_1 A_2} \\ &= [5.03\%]_{\text{Total}}\end{aligned}$$

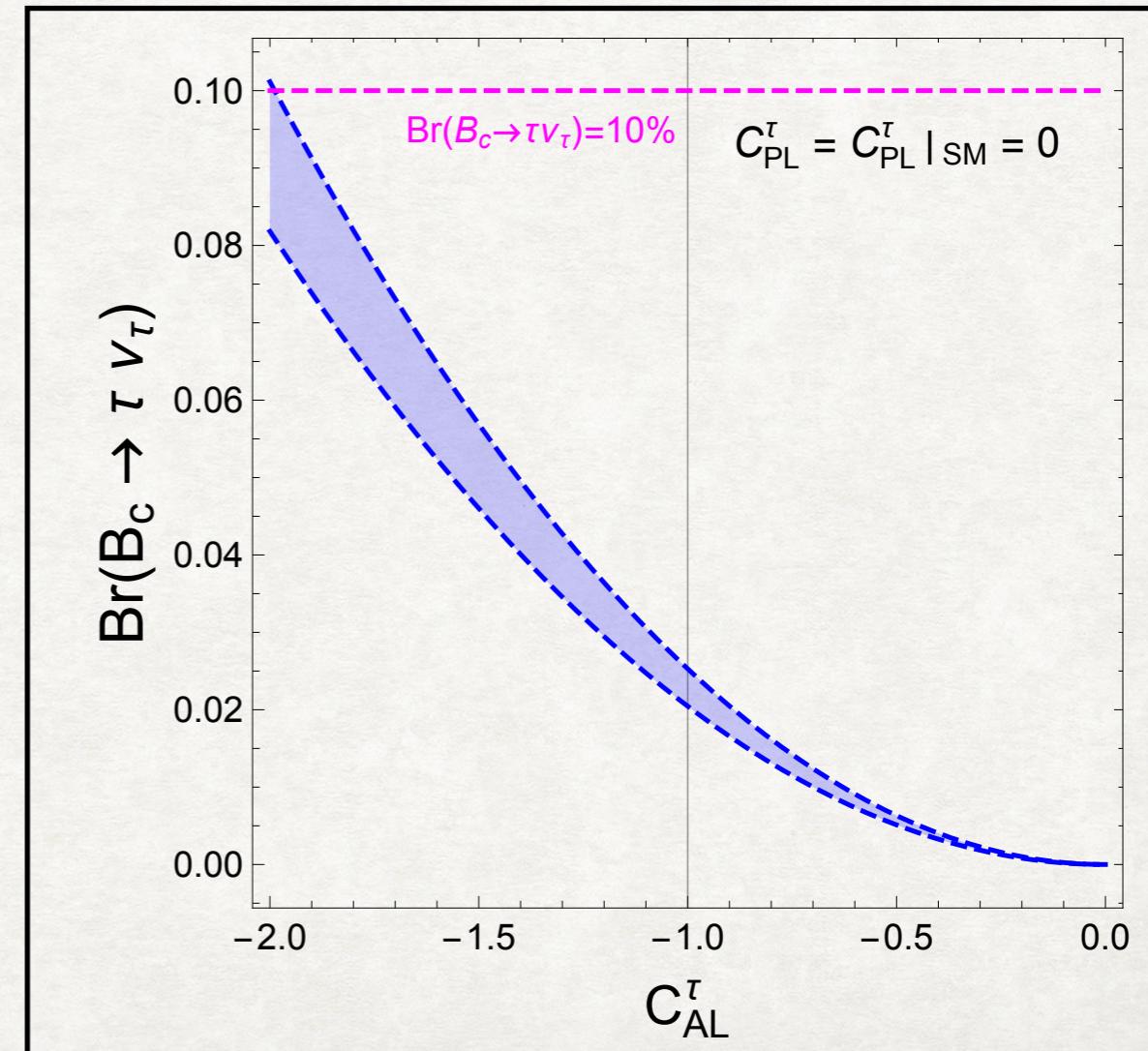
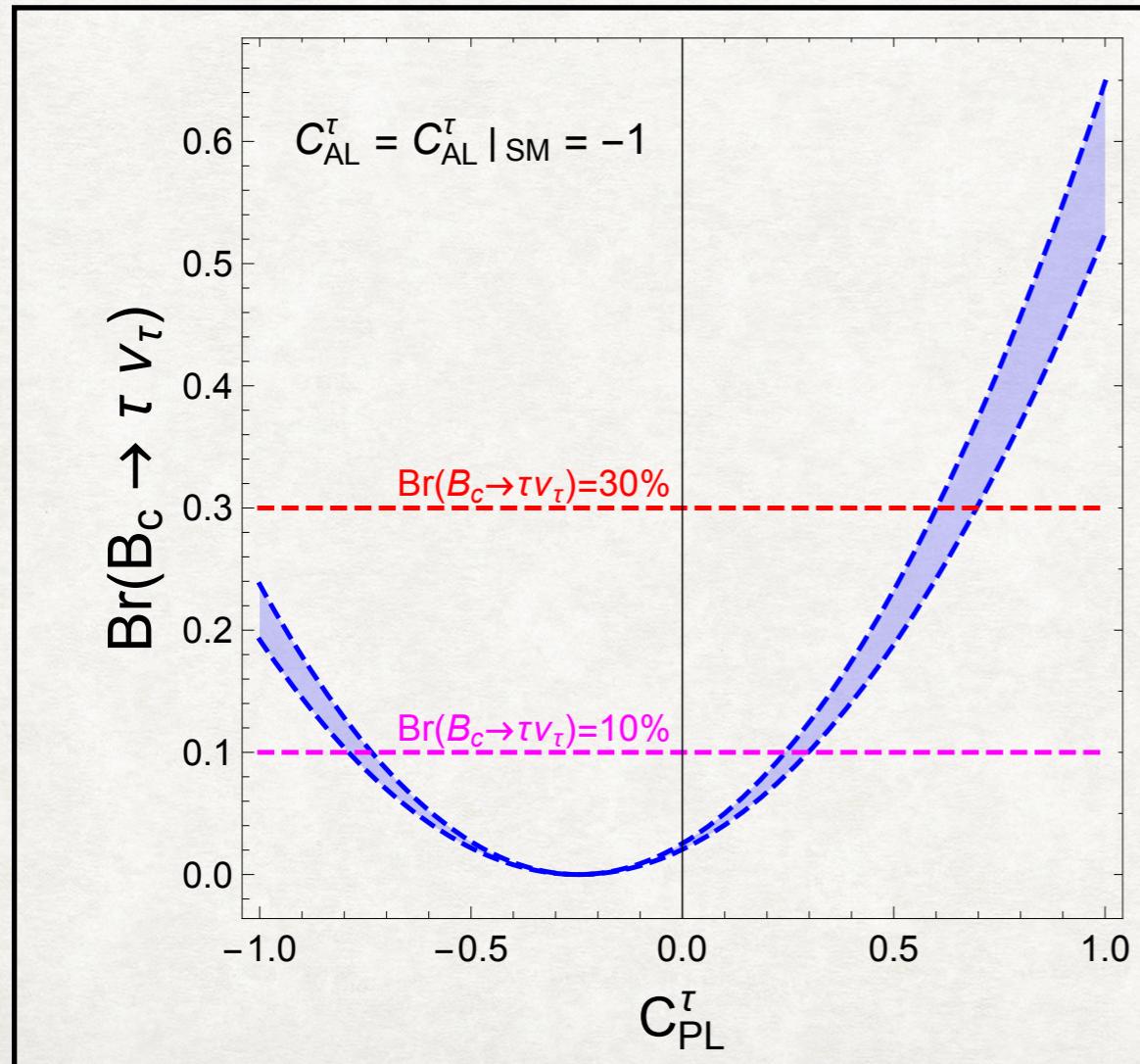
The Tensor Explanation



Branching Ratio of $B_c \rightarrow \tau\nu$

Relevant operators: C_{AL}^τ C_{PL}^τ C_{AR}^τ C_{PR}^τ

$$\mathcal{B}(B_c^- \rightarrow \tau^-\bar{\nu}_\tau) = \frac{1}{8\pi} G_F^2 |V_{cb}|^2 f_{B_c}^2 m_\tau^2 m_{B_c} \tau_{B_c} \left(1 - \frac{m_\tau^2}{m_{B_c}^2} \right)^2 \left(\left| C_{AL}^{cb\tau} - \frac{m_{B_c}^2}{m_\tau(m_b + m_c)} C_{PL}^{cb\tau} \right|^2 + \left| C_{AR}^{cb\tau} - \frac{m_{B_c}^2}{m_\tau(m_b + m_c)} C_{PR}^{cb\tau} \right|^2 \right)$$



Flavour to Mass eigenbasis

$$\begin{aligned}
 & [C_{\phi l}^{(3)}]_{p' r'}' \left(\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi \right) \left(l'_{p'} \sigma^I \gamma^\mu l'_{r'} \right) \\
 & \approx [C_{\phi l}^{(3)}]_{p' r'}' \left[-\frac{1}{2} \frac{g_2}{\cos\theta_W} Z_\mu \left(\bar{\nu}'_p \gamma^\mu P_L \nu'_r \right) + \frac{1}{2} \frac{g_2}{\cos\theta_W} Z_\mu \left(\bar{e}'_p \gamma^\mu P_L e'_r \right) - \frac{g_2}{\sqrt{2}} W_\mu^+ \left(\bar{\nu}'_p \gamma^\mu P_L e'_r \right) - \frac{g_2}{\sqrt{2}} W_\mu^- \left(\bar{e}'_p \gamma^\mu P_L \nu'_r \right) \right] \\
 & = [C_{\phi l}^{(3)}]_{p' r'}' \left[-\frac{1}{2} \frac{g_2}{\cos\theta_W} (V_L^\nu)_{pp'}^\dagger (V_L^\nu)_{r'r} Z_\mu \left(\bar{\nu}_p \gamma^\mu P_L \nu_r \right) + \frac{1}{2} \frac{g_2}{\cos\theta_W} (V_L^e)_{pp'}^\dagger (V_L^e)_{r'r} Z_\mu \left(\bar{e}_p \gamma^\mu P_L e_r \right) \right. \\
 & \quad \left. - \frac{g_2}{\sqrt{2}} (V_L^\nu)_{pp'}^\dagger (V_L^e)_{r'r} W_\mu^+ \left(\bar{\nu}_p \gamma^\mu P_L e_r \right) - \frac{g_2}{\sqrt{2}} (V_L^e)_{pp'}^\dagger (V_L^\nu)_{r'r} W_\mu^- \left(\bar{e}_p \gamma^\mu P_L \nu_r \right) \right]
 \end{aligned}$$

Gauge basis

Mass basis

Put constraints on these operators