New physics in $b \to (c, u)\tau\nu$ transitions

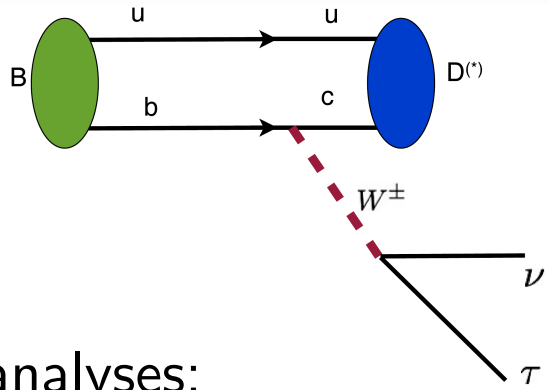
Martin Jung

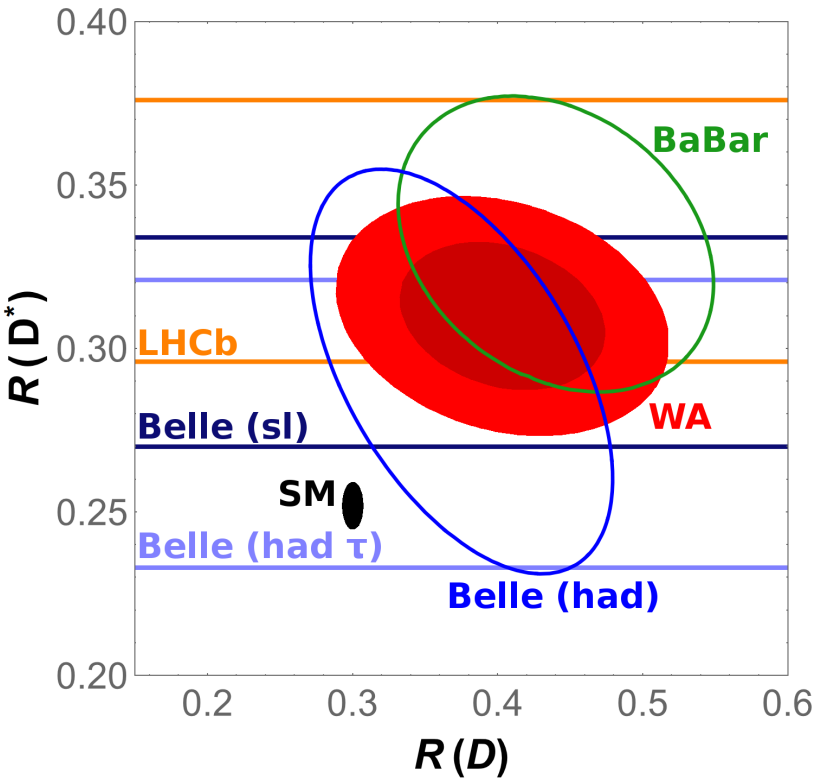
Talk at "New physics at the junction of flavor and collider phenomenology"
Portorož, Slovenia, 18th of April 2017

Experimental Situation for $b \to c\tau\nu$ 2017

Importance of semi-leptonic decays:

- Minimal hadronic input, improvable!
  $R(D^{(*)}) \equiv \frac{\mathrm{Br}(B \to D^{(*)}\ell\nu)}{\mathrm{Br}(B \to D^{(*)}\tau\nu)}$
- NP: Relative to tree, τ least constrained





contours: 68% CL
filled: 95(68)% CL

4 recent $R(D^{(*)})$ analyses:

- $R(D^*)$ from LHCb [1506.08614]
- Belle update + new measurement (had./sl tag) [1507.03233,1603.06711] , τ-polarization + $R(D^*)(\tau \to \text{had})$ [1608.06391]

➥ 4.0σ tension [HFAG]

Further $b \to c\tau\nu$ inputs:

- Differential rates from Belle, BaBar
- Total width of B_c
- ($b \to X_c\tau\nu$ by LEP)

SM predictions [see also Paolo's talk]

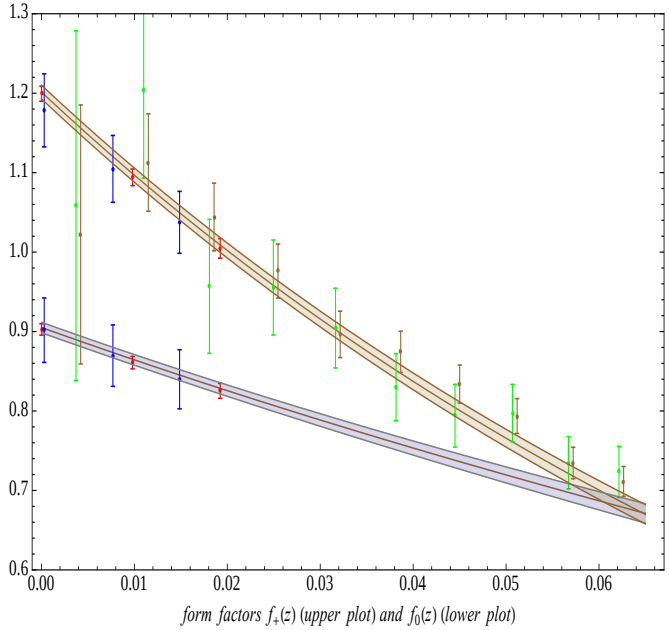
SI amplitude: kinematics $\times$ FC coupling (SM: CKM) $\times$ form factor

> Strategy SM predictions: V_{cb} + leading FF cancels
> data + theoretical input from LQCD/HQET for FF ratios

$B \to D$: 2 form factors $f_{+,0}$

- Data determines shape of $f_+(q^2)$
- LQCD required for f_0: fit HPQCD + FNAL/MILC, use $f_+(0) = f_0(0)$

➥ $R(D) = 0.301 \pm 0.003$ [Bigi/Gambino'16]



$B \to D^*$: 4 form factors $V, A_{0,1,2}$

- 3/4 $\to$ data (+HQET, unitarity $\to$ CLN)
- HQET for A_0 [Falk/Neubert] , enhance uncertainty [Fajfer/Kamenik]

➥ $R(D^*) = 0.252 \pm 0.003$, (0.257 from re-analysis [Bernlochner+'17])

- LQCD for non-maximal recoil underway

(Very) good control, effect too large to be in CLN relations

Charged scalar effects in (semi-)leptonic decays

Effective Theory for $b \to c\tau\nu$ transitions (SM: $C_{V_L} = 1, C_{i \neq V_L} = 0$):

$$\mathcal{L}_{\text{eff}}^{b \to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j^5 C_j \mathcal{O}_j \,, \qquad \text{with}$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)\bar{\tau}\gamma_\mu \nu \,,\ \mathcal{O}_{S_{L,R}} = (\bar{c} P_{L,R} b)\bar{\tau}\nu \,,\ \mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)\bar{\tau}\sigma_{\mu\nu}\nu \,.$$

A charged scalar generally results in ($C_{S_{L,R}}$ can be complex):
NP couplings $C_{S_{L,R}}$, $C_{V_L} = C_{V_L}^{\text{SM}} = 1$, $C_{V_R} = C_T = 0$

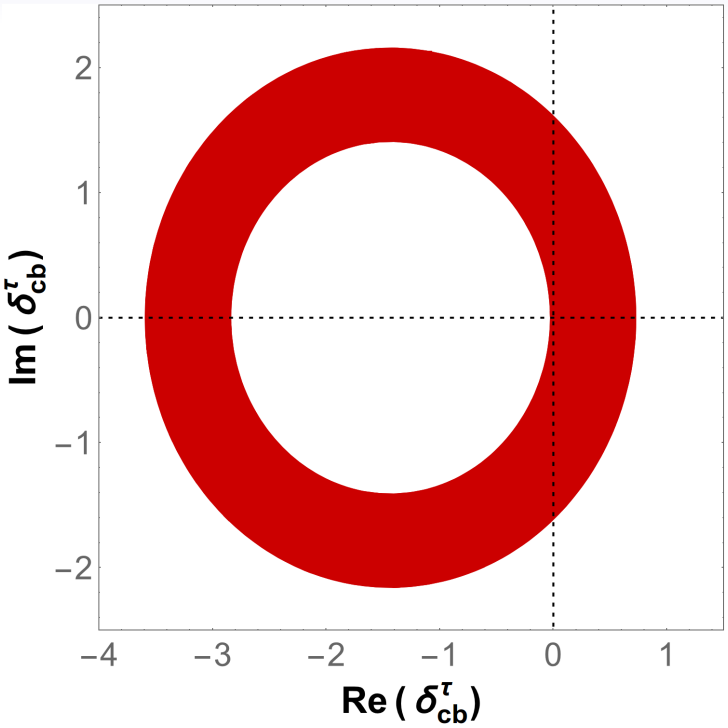
- Model-independent subclass as long as $C_{S_{L,R}}$ general
- Phenomenologically $C_{SL,R}^{q_u q_d l} \sim m_{q_{ud}} m_l$ (e.g. Type III)

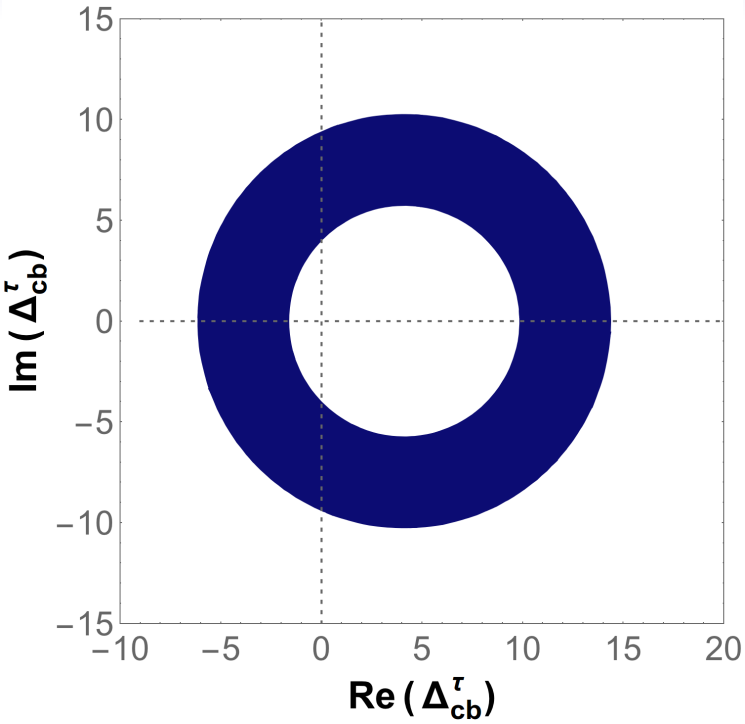
Appearing combinations:

$$R(D) : \delta^{cbl} \equiv \frac{(C_{S_L} + C_{S_R})(m_B - m_D)^2}{m_l(\bar{m}_b - \bar{m}_c)} \qquad R(D^*) : \Delta^{cbl} \equiv \frac{(C_{S_L} - C_{S_R}) m_B^2}{m_l(\bar{m}_b + \bar{m}_c)}$$

Can trivially explain $R(D^{(*)})$! Exclusion possible with specific flavour structure or more $b \to c\tau\nu$ observables!

$b \to c\tau\nu$ data and scalar NP

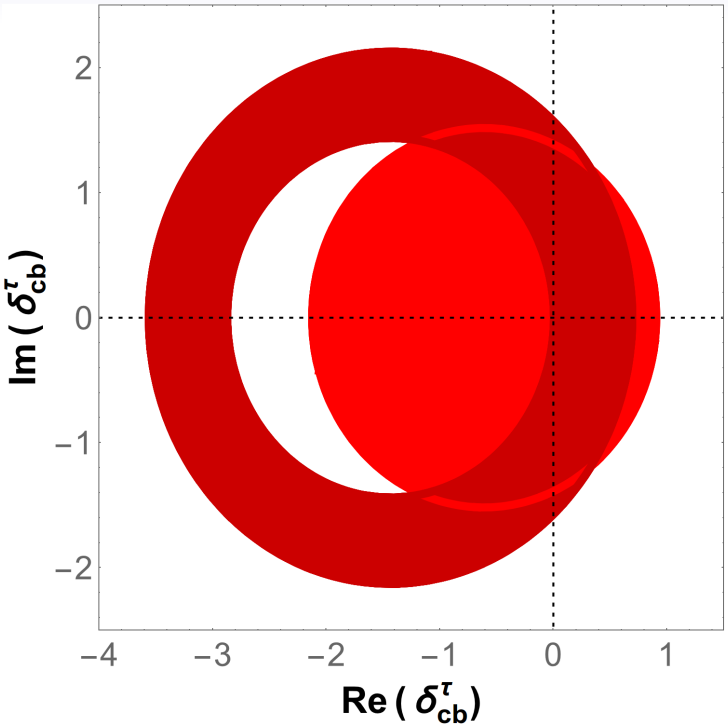


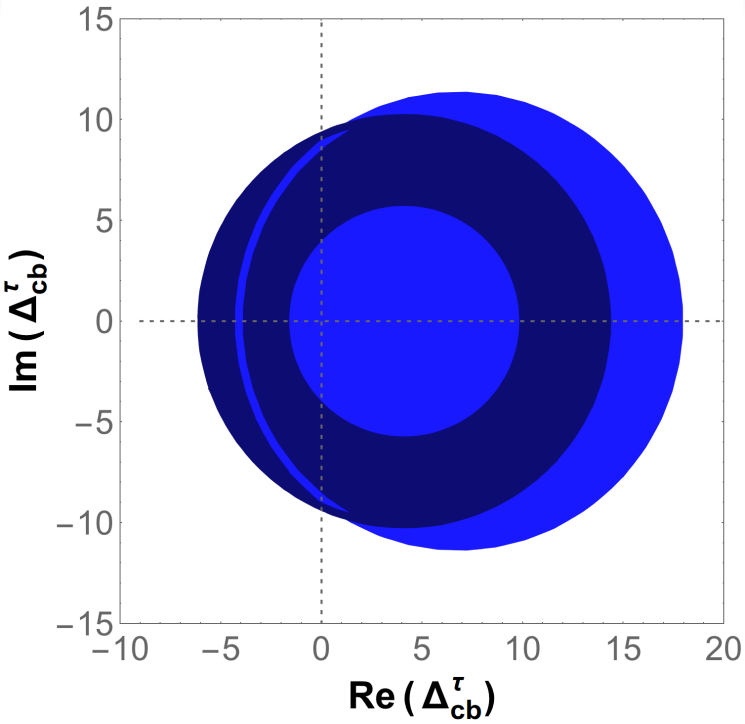


$R(D), R(D^*)$:

- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge ($|C_{S_L} - C_{S_R}| \sim 1 - 5$)

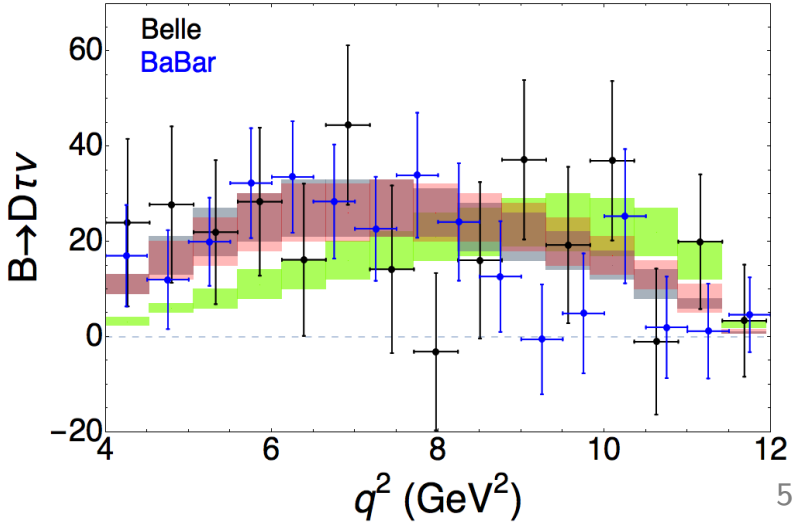
$b \to c\tau\nu$ data and scalar NP



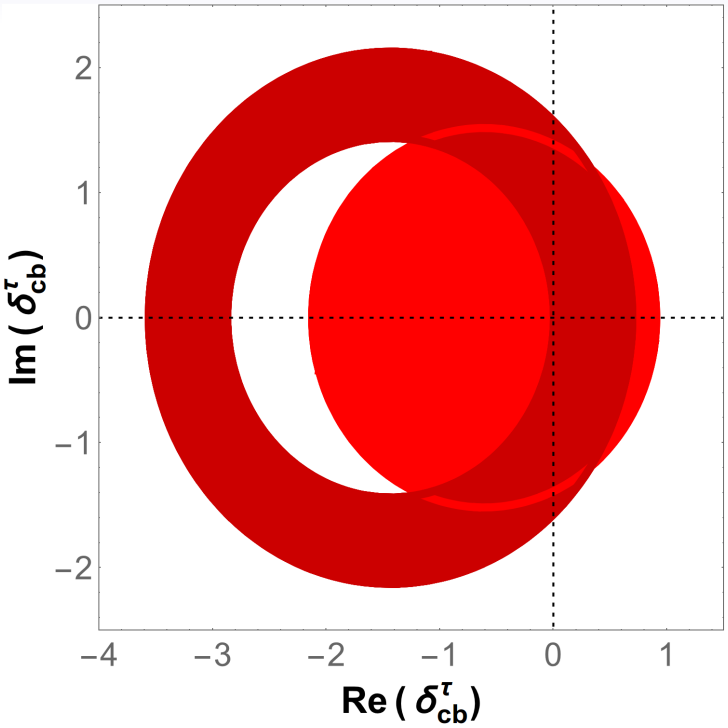


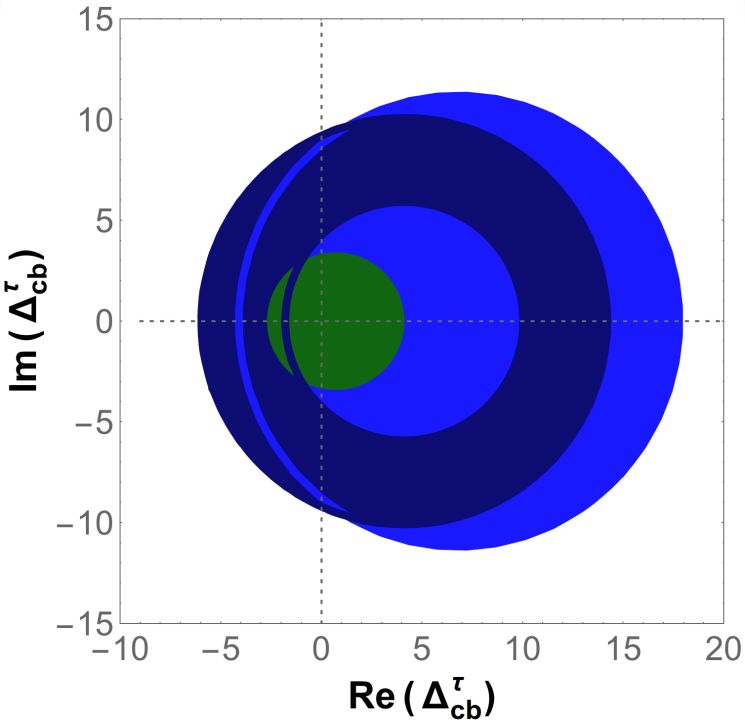
Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \to D\tau\nu$
- exclude 2nd real solution in δ^τ_{cb}



$b \to c\tau\nu$ data and scalar NP

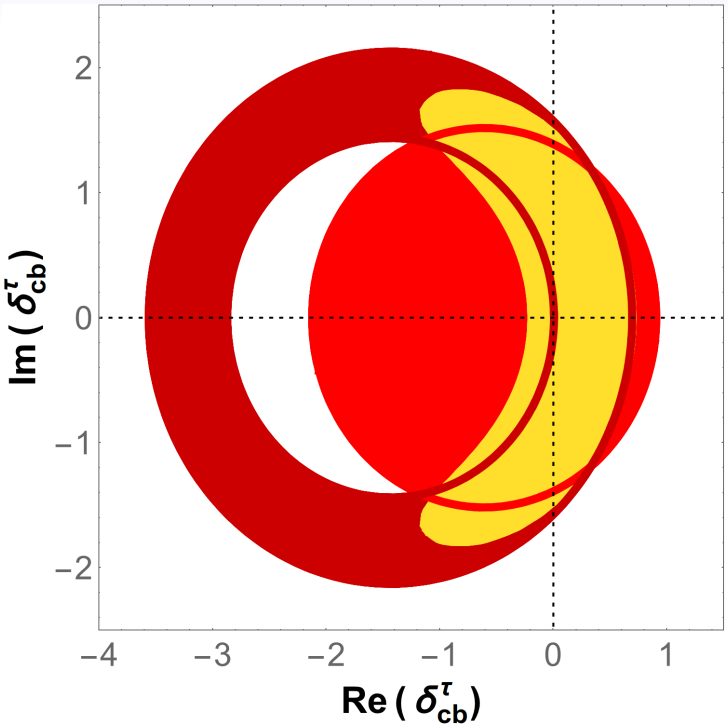


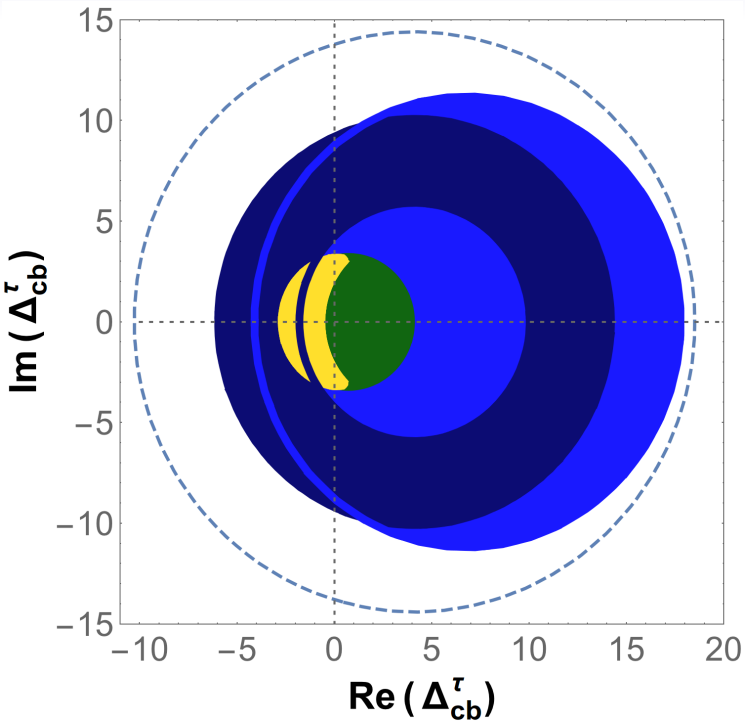


Total width of B_c:

- $B_c \to \tau\nu$ is an obvious $b \to c\tau\nu$ transition
  - ➥ not measurerable in foreseeable future
  - ➥ can oversaturate total width of B_c! [X.Li+'16]
- Excludes second real solution in Δ^τ_{cb} plane (even scalar NP for $R(D^*)$? [Alonso+'16])

$b \to c\tau\nu$ data and scalar NP





τ polarization:

- So far not constraining (shown: $\Delta\chi^2 = 1$)
- Differentiate NP models: with scalar NP [Celis/MJ/Li/Pich'13]

$$X_2^{D^{(*)}}(q^2) \equiv R_{D^{(*)}}(q^2)\left[A_\lambda^{D^{(*)}}(q^2) + 1\right] = X_{2,SM}^{D^{(*)}}(q^2)$$

Consistent explanation in 2HDMs possible, flavour structure?

Generic features and issues in 2HDMs

Charged Higgs possible as explanation of $b \to c\tau\nu$ data...
However, typically expect $\Delta R(D^*) < \Delta R(D)$

Generic feature: Relative influence larger in leptonic decays!

- No problem in $b \to c\tau\nu$ since $B_c \to \tau\nu$ won't be measured
- Large charm coupling required for $R(D^*)$

➥ Embedding $b \to c\tau\nu$ into a viable model complicated!
➥ $D_{d,s} \to \tau, \mu\nu$ kill typical flavour structures with $C_{S_{L,R}} \sim m$
➥ Only fine-tuned models survive all (semi-)leptonic constraints

$b \to s\ell\ell$ very complicated to explain with scalar NP
➥ 2HDM alone tends to predict $b \to s\ell\ell$ to be QCD-related

$b\bar{b} \to (H, A) \to \tau^+\tau^-$ poses a severe constraint [Faroughy+'16, Admir's talk]

2HDMs strongly prefer a smaller value for $R(D^*)$!

Differentiating models with $b \to c\tau\nu$ observables [LQ: Andi C.]

Large $R(D^*)$ possible with NP in V_L ($\hat{R}(X) = R(X)/R(X)_{SM}$):

- trivial prediction: $\hat{R}(D) = \hat{R}(D^*) = \hat{R}(\Lambda_c) = \ldots \overset{exp}{\sim} 1.25$
- can be related to anomaly in $B \to K^{(*)}\ell^+\ell^-$ modes
- $\hat{R}(X_c) = 0.99 \pm 0.10$ measured by LEP, oversaturation
- issues with $\tau \to \mu\nu\nu$ [Feruglio+'16] and $b\bar{b} \to X \to \tau^+\tau^-$ [Faroughy+'16]

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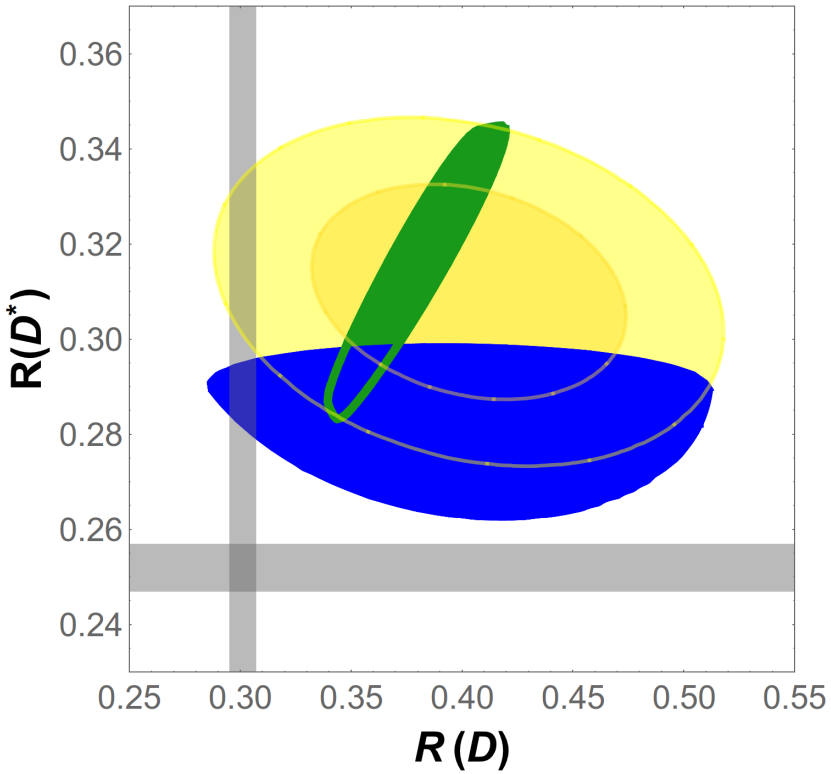
Fit results for the two scenarios for $B \to D^{(*)}\tau\nu$:



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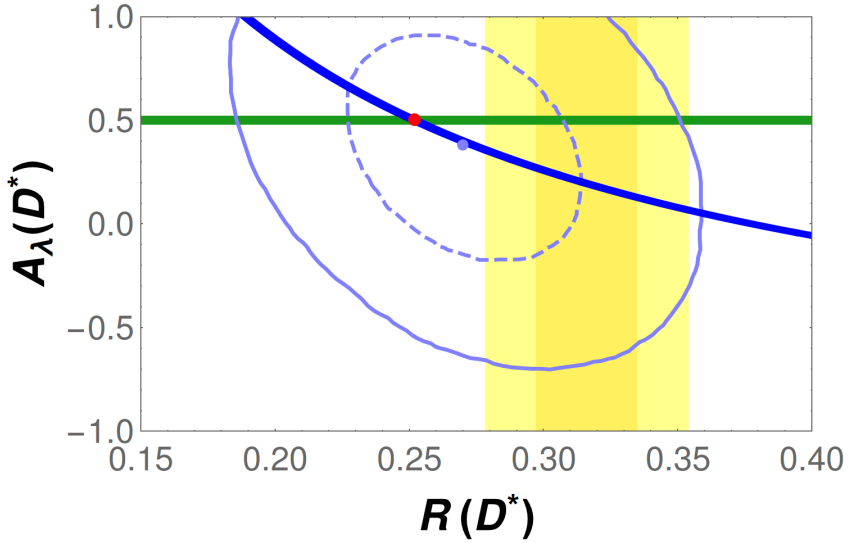
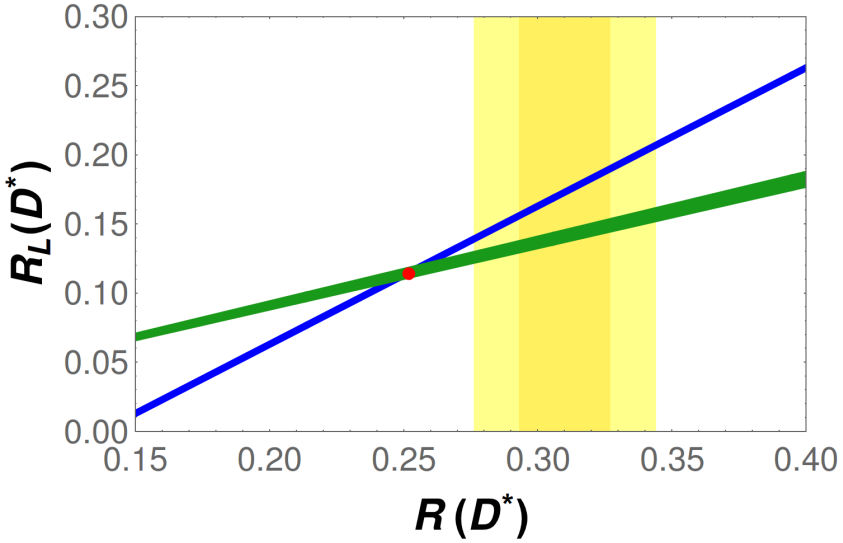
Fit predictions for polarization-dependent $B \to D^*\tau\nu$ observables:





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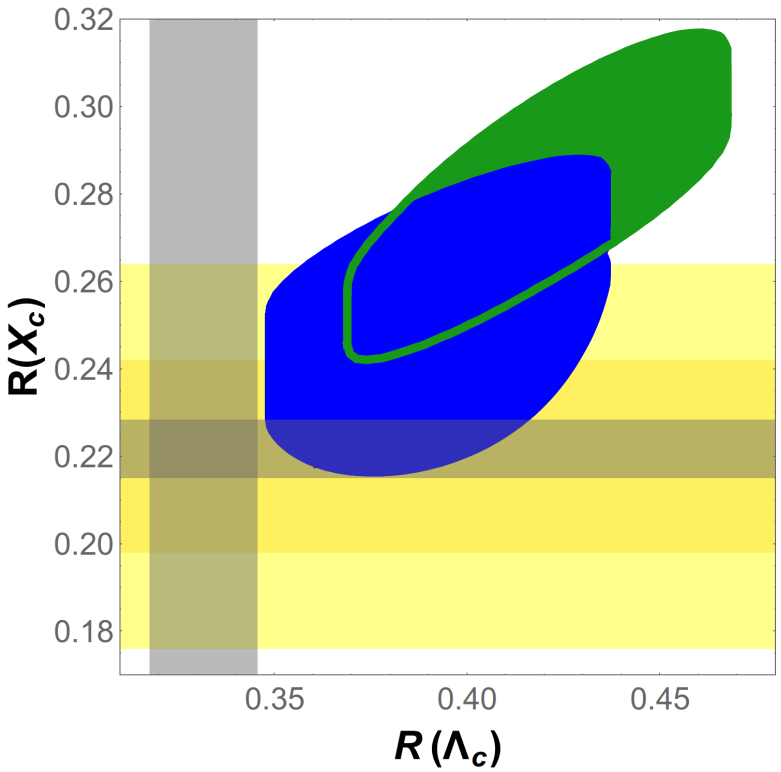
Fit predictions for $B \to X_c\tau\nu$ and $\Lambda_b \to \Lambda_c\tau\nu$:



NP in $b \to u\tau\nu$ transitions

$b \to u\tau\nu$ less explored experimentally, $|V_{ub}/V_{cb}|^2 \sim 1\%$:

- $R(\tau) \equiv BR(B \to \tau\nu)/BR(B \to \pi\ell\nu)$ about 1.8σ from SM
- $R(\pi)$ not significantly measured yet

➥ Data consistent with SM as well as sizable NP

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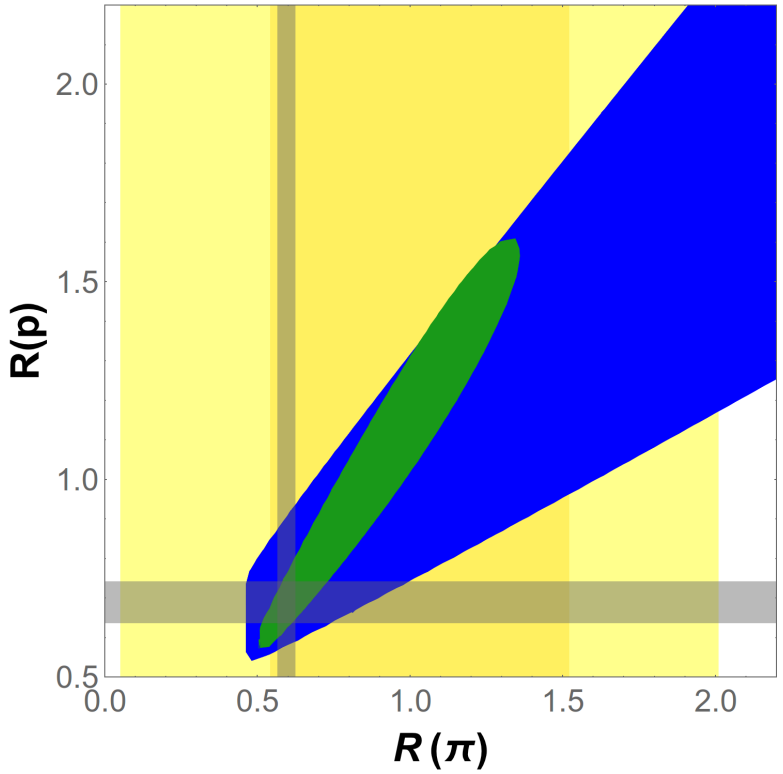
Analyse $b \to u\tau\nu$ individually:

➥ $R(\tau)$ yields correlation between $R(\pi)$ and $R(p)$



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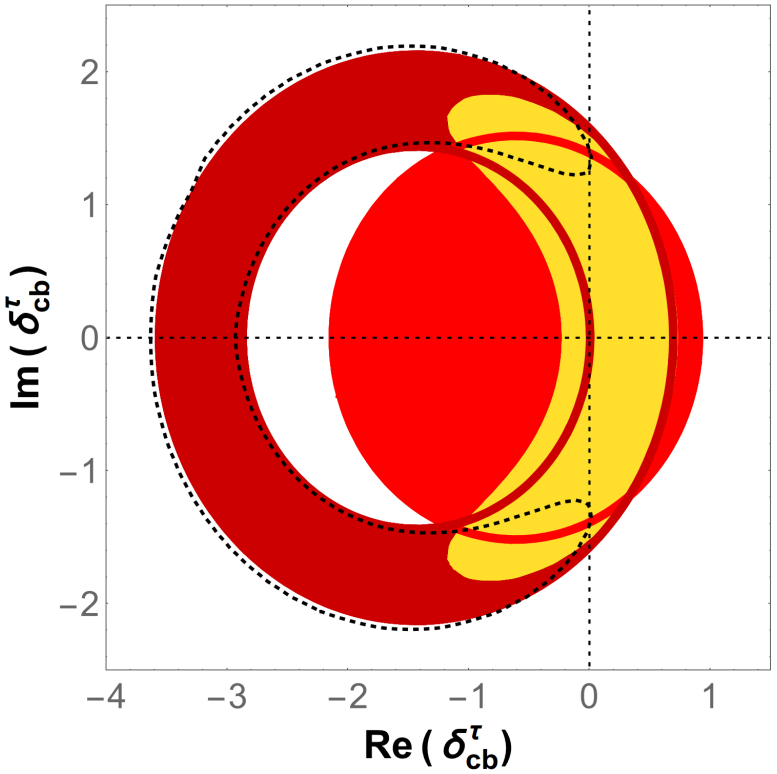
Assume universality ($Y_1^{u,d} \sim Y_2^{u,d}$), as e.g. in Type II:

➥ $R(\tau)$ yields additional tension



Conclusions

$b \to c\tau\nu$: indications of lepton-non-universal NP

- New measurements/observables constrain NP more severely
- Scalar NP possible solution (only 1 real solution):
  - tensions with $\Gamma(B_c)$, $b\bar{b} \to \tau^+\tau^-$
- NP with LH vector couplings: address also $b \to s\ell\ell$
  - Can accomodate large $R(D^*)$
  - tensions with $\hat{R}(X_c)$, $b\bar{b} \to \tau^+\tau^-$, $\tau \to \mu\nu\bar{\nu}/\mu \to e\nu\bar{\nu}$
- Smaller $R(D^*)$ would improve both interpretations
- The problem can be solved experimentally with more data
  - Additional observables in $B \to D^{(*)}\tau\nu$, *e.g.* A_λ, $d\Gamma/dq^2$, ...
  - Observables in other channels, e.g. $R(X_c)$, $R(\Lambda_c)$
- Testing flavour structure with $b \to u\tau\nu$:
  - $R(\tau)$ correlates $R(\pi)$ and $R(p)$
  - Again differentiation possible, more data needed!

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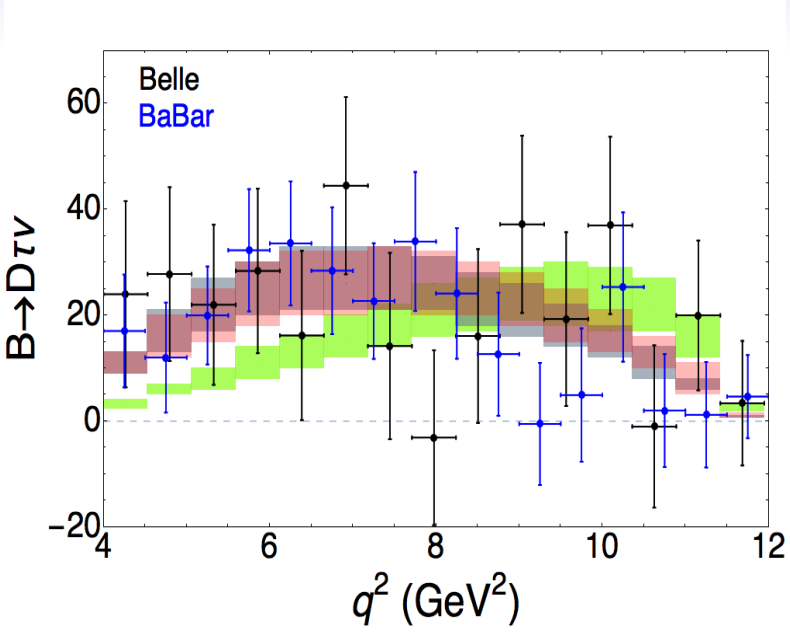
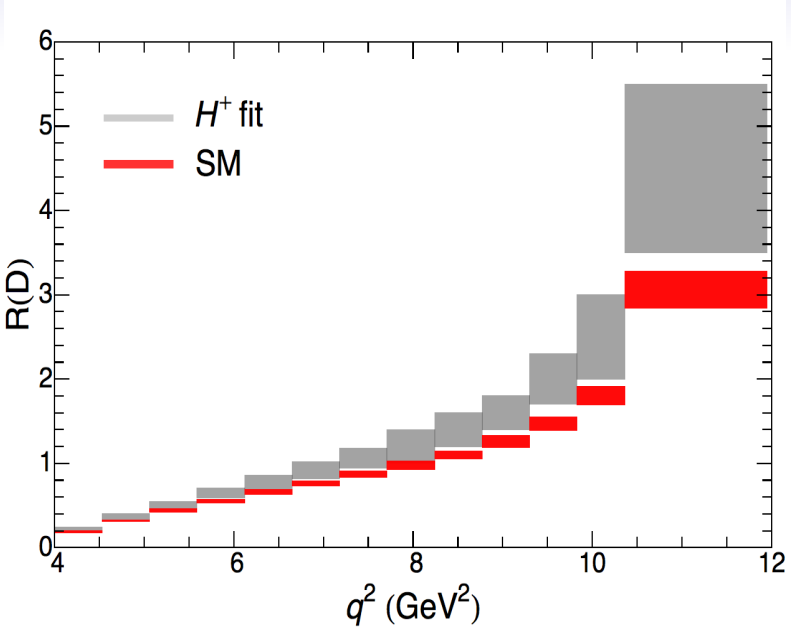
Thank you for your attention!

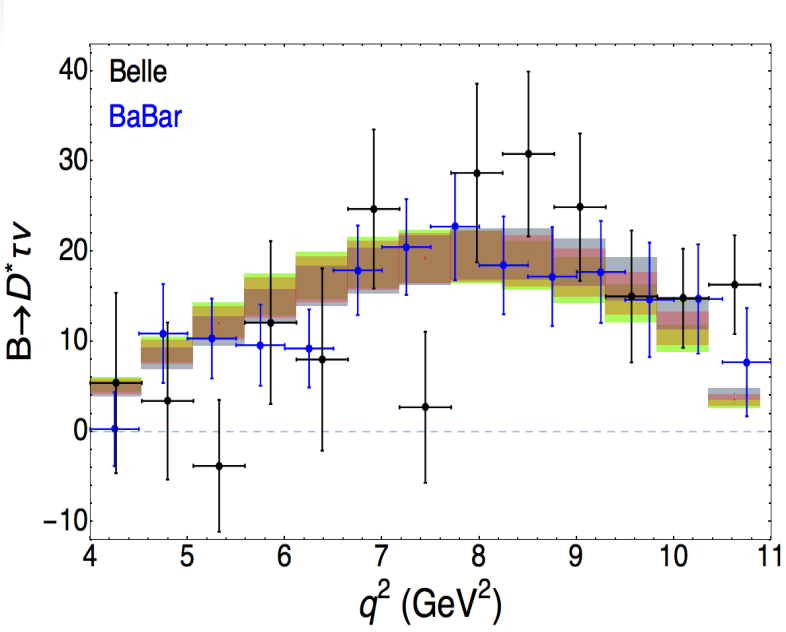
The differential distributions $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$

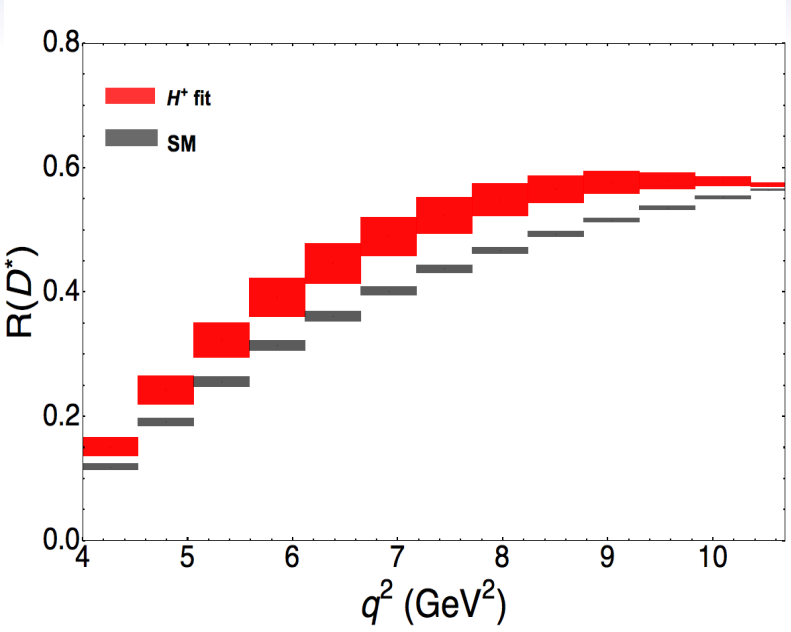




- Data stat. uncertainties only, BaBar rescaled
- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D)$
  Red: SM fit (distributions only)
  Green: Allowed by $R(D)$, excluded by distribution
- Need better experimental precision, ideally $dR(D)/dq^2$
- Parts of NP parameter space clearly excluded

The differential distributions $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$





- Data stat. uncertainties only, BaBar rescaled
- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D^*)$
  Red: SM fit (distributions only)
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- Need better experimental precision, ideally $dR(D^*)/dq^2$
- Not very restrictive at the moment

Implications of the Higgs EFT for Flavour: $q \to q'\ell\nu$

$b \to c\tau\nu$ transitions (SM: $C_{V_L} = 1, C_{i\neq V_L} = 0$):

$$\mathcal{L}_{\rm eff}^{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j^5 C_j \mathcal{O}_j \,, \qquad \text{with}$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)\bar{\tau}\gamma_\mu \nu \,, \qquad \mathcal{O}_{S_{L,R}} = (\bar{c} P_{L,R} b)\bar{\tau}\nu \,,$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)\bar{\tau}\sigma_{\mu\nu}\nu \,.$$

- All operators are independently present already in the linear EFT
- However: Relations between different transitions:
  C_{V_R} is lepton-flavour universal [see also Cirigliano+'09]
  Relations between charged- and neutral-current processes, *e.g.*
  $\sum_{U=u,c,t} \lambda_{Us} C_{S_R}^{(U)} = -\frac{e^2}{8\pi^2} \lambda_{ts} C_S^{(d)}$ [see also Cirigliano+'12,Alonso+'15]
- These relations are again absent in the non-linear EFT

Matching for $b \to c\ell\nu$ transitions

$$
\begin{aligned}
C_{V_L} &= -\mathcal{N}_{\rm CC}\left[C_L + \frac{2}{v^2}c_{V5} + \frac{2V_{cb}}{v^2}c_{V7}\right], \\
C_{V_R} &= -\mathcal{N}_{\rm CC}\left[\hat{C}_R + \frac{2}{v^2}c_{V6}\right], \\
C_{S_L} &= -\mathcal{N}_{\rm CC}\left(c'_{S1} + \hat{c}'_{S5}\right), \\
C_{S_R} &= 2\,\mathcal{N}_{\rm CC}\left(c_{LR4} + \hat{c}_{LR8}\right), \\
C_T &= -\mathcal{N}_{\rm CC}\left(c'_{S2} + \hat{c}'_{S6}\right),
\end{aligned}
$$

where $\mathcal{N}_{\rm CC} = \frac{1}{2V_{cb}}\frac{v^2}{\Lambda^2}$, $C_L = 2c_{LL2} - \hat{c}_{LL6} + \hat{c}_{LL7}$ and $\hat{C}_R = -\frac{1}{2}\hat{c}_{Y4}$.

List of minimal χ^2 values

Scenario	$\chi^2_{\rm min}$	# obs.	# pars.	central values (δ^τ_{cb}, Δ^τ_{cb})
		$R(D^{(*)})$ only		
SM	23.1	2	0	—
S1	0	2	4	$(0.2+0.7i, 10.0-6.3i)$
S1 real	0	2	2	$(0.4, -3.6)$
$g_L^{cb\tau}$	0	2	2	$g_L^{cb\tau} = -1.3-0.6i$
$g_R^{cb\tau}$	9.1	2	2	$g_R^{cb\tau} = 0.3+0.i$
g_{V_L}	0.2	2	1	$\lvert g_{V_L}\rvert = 1.12$
		$R(D^{(*)})$, $d\Gamma/dq^2$, Γ_{B_c}		
SM	65.9	61	4	—
S1	49.2	61	8	$(0.4+0.i, -2.4+0.i)$
S1 real	49.2	61	6	$(0.4, -2.4)$
$g_L^{cb\tau}$	55.4	61	6	$g_L^{cb\tau} = -0.4+0.8i$
$g_R^{cb\tau}$	55.4	61	6	$g_R^{cb\tau} = 0.3+0.i$
g_{V_L}	42.4	61	5	$\lvert g_{V_L}\rvert = 1.12$
		$R(D^{(*)})$, $d\Gamma/dq^2$, Γ_{B_c}, $R(X_c)$		
SM	65.9	62	4	—
S1	50.4	62	8	$(0.3+0.i, -2.4+0.i)$
S1 real	50.4	62	6	$(0.3, -2.4)$
$g_L^{cb\tau}$	55.4	62	6	$g_L^{cb\tau} = -0.4-0.8i$
$g_R^{cb\tau}$	56.1	62	6	$g_R^{cb\tau} = 0.2+0.i$
g_{V_L}	46.7	62	5	$\lvert g_{V_L}\rvert = 1.10$