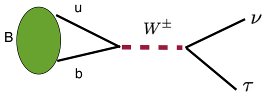
Theory prospects with $b \to c(u)\ell\nu$ transitions

Martin Jung

"Beyond the LHCb Phase-1 Upgrade"

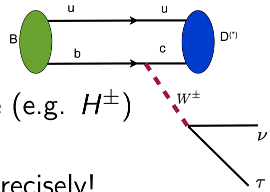
La Biodola, Italy, 29th of May 2017

Importance of (semi-)leptonic hadron decays



In the Standard Model:

- Determination of $|V_{ij}|$ (7/9)



Beyond the Standard Model:

- Leptonic decays $\sim m_l^2$
  - ➥ large relative NP influence possible (e.g. $H^\pm$)
- NP in semi-leptonic decays moderate
  - ➥ Need to understand the SM very precisely!
- NP: Relative to tree, τ least constrained

Key advantages:

- Large rates
- Minimal hadronic input
- ➥ This input is systamatically improvable

Additionally: (almost) all flavour anomalies involve leptons

Generalities

If $R(D, D^*)$ are real, they will be established before 2nd upgrade

Consequently the objectives change:

- Differentiation between structures in $b \to c\tau\nu$
  - ➥ Distributions in q^2 + angles, polarization of τ, D^*
- Flavour structure on the lepton side ($\to \mu$ vs. e)
  - ➥ improvements for electrons?
- Flavour structure on the quark side (e.g. $b \to u$ vs. $b \to c$)
  - ➥ Possibilities in charm decays? (not part of this talk)

A lot of this is not yet done, insufficient data
Close collaboration of experiment and theory necessary

Objectives of this talk:

- Examples of challenging systematics (th + exp)
- Status of present tensions
- Identification of "clean" observables with differentiating power

New systematics: BR measurements and isospin violation

Branching ratio measurements require normalization...

- B factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from B factories

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Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: (mostly) assumes $f_u \equiv f_d$, uses $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$

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Both approaches problematic: [MJ'16 [1510.03423]]

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in r_{+0}^{HFAG} assume isospin in exclusive decays
  - ➥ This is one thing we want to test!

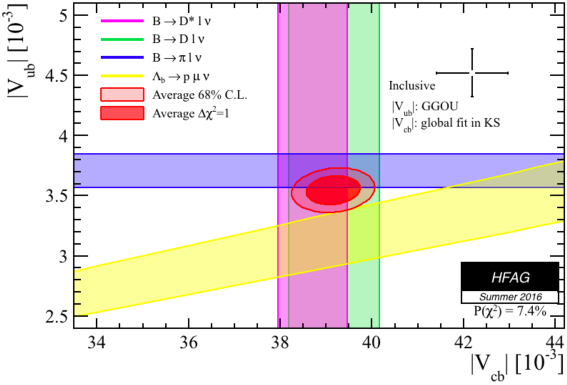
➥ Avoiding this assumption yields $r_{+0} = 1.027 \pm 0.037$

- Isospin asymmetries test NP with $\Delta I = 1, 3/2$ (e.g. $b \to s\bar{u}u$)
  - ➥ Isospin asymmetry $B \to J/\psi K$: $A_I = -0.009 \pm 0.024$

Affects every percent-level BR measurement
$B \to J/\Psi K$ can be used to determine f_u/f_d!

$|V_{xb}|$: inclusive versus exclusive

Long-standing problem:



- Very hard to explain by NP [Crivellin/Pokorski'15]
  (but see [Colangelo/de Fazio'15])

➥ Likely experimental/theoretical systematics

$|V_{xb}|$: Recent developments

V_{cb}:

Recent Belle $B \to D, D^*\ell\nu$ analyses

Recent lattice results for $B \to D$

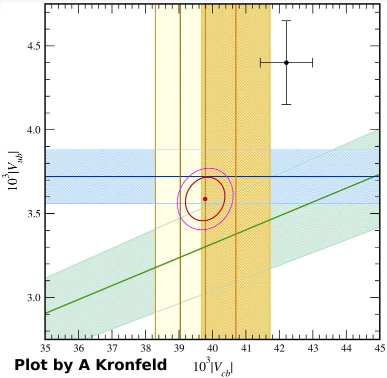
[FNAL/MILC, HPQCD, RBC/UKQCD (ongoing)]

- $B \to D$ between incl. + $B \to D^*$

New lattice result for $B \to D^*$ [HPQCD]

- $V_{cb}^{\rm incl}$ cv, compatible with old result

$B \to D^*\ell\nu$ re-analyses with CLN, $|V_{cb}| = 39.3(1.0)10^{-2}$ [Bernlochner+'17] + BGL [Bigi+,Grinstein+'17] (Belle only), $|V_{cb}| = 40.4(1.7)10^{-2}$

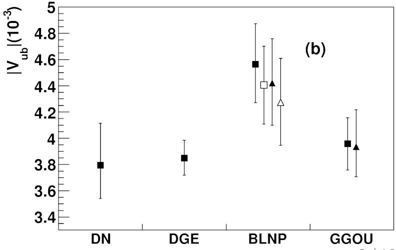


Plot by A Kronfeld

New BaBar analysis of V_{ub} incl.:

Dependence on theory treatment!

- GGOU 2σ lower than WA
- Compatible w/ PDG exclusive avg



Hints towards resolution, not yet conclusive

Prospects $b \to (u, c)(e, \mu)$ @ LHCb

Potential unambiguous $|V_{xb}|$ determination before phase-II upgrade

➥ Measuring $b \to u, c\ell\nu$ not about this

Instead, model-independent determinations of NP contributions

- If FNU in $b \to c$ is confirmed, expect "something" in $b \to u$
- Also, with $b \to c\tau\nu$ affected, μ vs. e important to check
- Universality checks of right-handed currents interesting

$|V_{ub}/V_{cb}|$ from Λ_b important ingredient right now...

- Tests different NP combinations than mesonic modes
- Which observables are measurable?
- How much can we reduce the systematics?
- FFs need improvement, but not the main issue

$B_s \to K\ell\nu$ essentially probes the same physics as $B \to \pi\ell\nu$

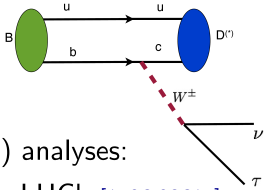
➥ direct competition with Belle II

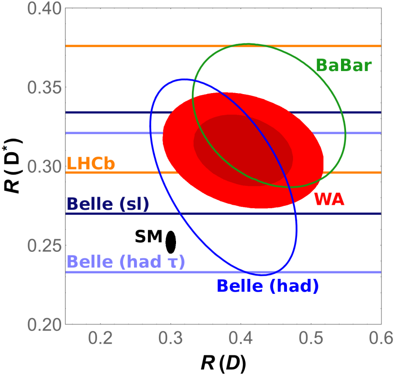
$B \to pp\ell\nu$ interesting new idea

➥ Challenging, qualititative theory progress required!

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

$$R(X) \equiv \frac{\mathrm{Br}(B \to X\tau\nu)}{\mathrm{Br}(B \to X\ell\nu)}$$





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 Zoltan's talk]

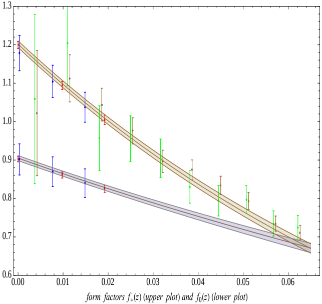
Sl amplitude: kinematics × FC coupling (SM: CKM) × form factor

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 → data (+HQET, unitarity → 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

NP in (semi-)leptonic decays

EFT for $b \to c\tau\nu$ transitions (no light ν_R, SM: $C_{V_L} = 1, C_{i\neq V_L} = 0$):

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

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

NP models typically generate subsets; for a charged scalar:
NP couplings $C_{S_{L,R}}$ (complex), $C_{V_L} = C_{V_L}^{\rm SM} = 1$, $C_{V_R} = C_T = 0$

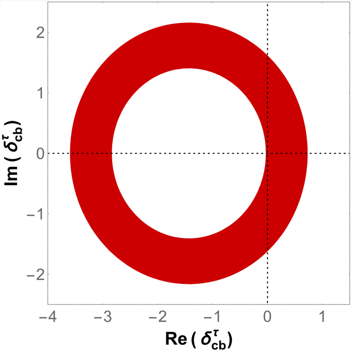
- Model-independent subclass as long as $C_{S_{L,R}}$ general
- Phenomenologically $C_{SL,R}^{q_u q_d l} \sim m_{q_{ud}} m_l$ (e.g. Type III)

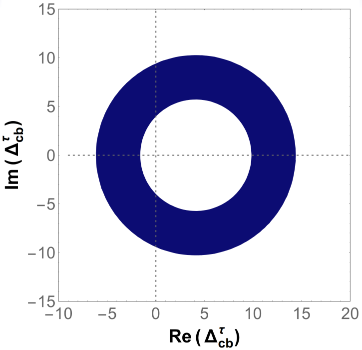
➡ Used to illustrate here, appearing combinations:

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

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 [Celis/MJ/Li/Pich'17]

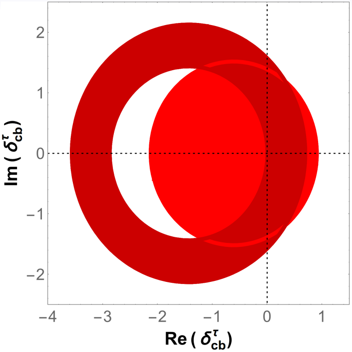


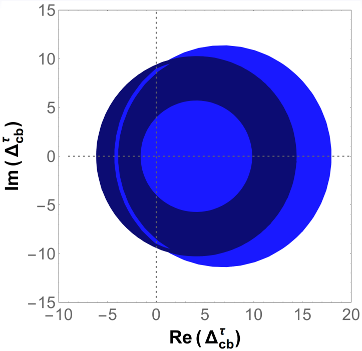


$R(D), R(D^*)$:

- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge ($|C_{S_L} - C_{S_R}| \sim 1-5$)
- Can't go beyond circles with just $R(D, D^*)$!

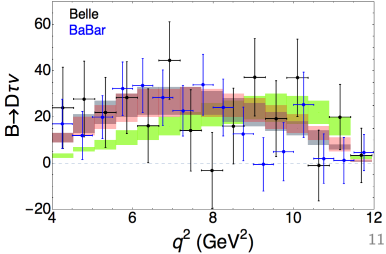
$b \to c\tau\nu$ data and scalar NP [Celis/MJ/Li/Pich'17]





Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \to D\tau\nu$
- "theory-dependence" of data needs addressing [Bernlochner+'17]



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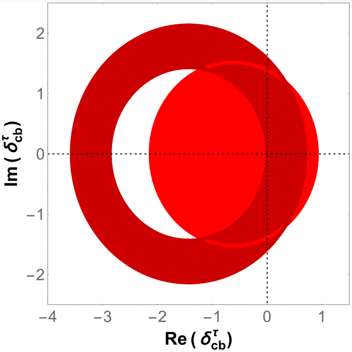

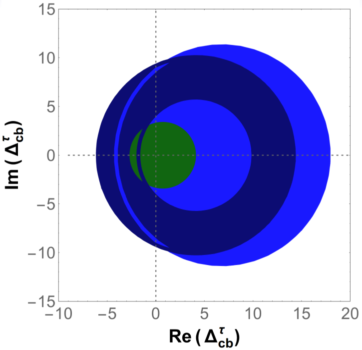

Total width of B_c:

- $B_c \to \tau\nu$ 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])

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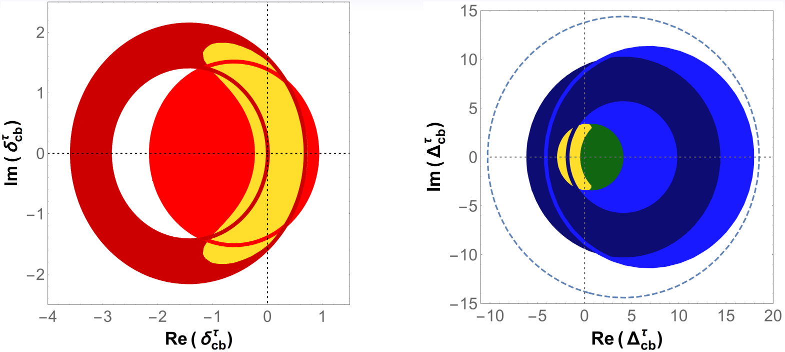

τ polarization:

- 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?

Differentiating models with $b \to c\tau\nu$ observables

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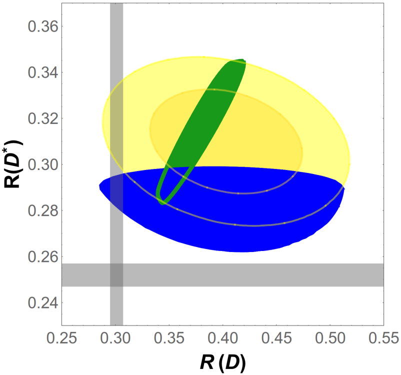
Fit results for the two scenarios for $B \to D^{(*)}\tau\nu$:



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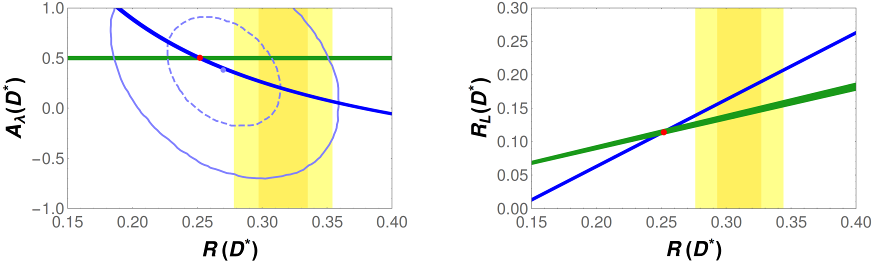
Fit predictions for polarization-dependent $B \to D^*\tau\nu$ observables:



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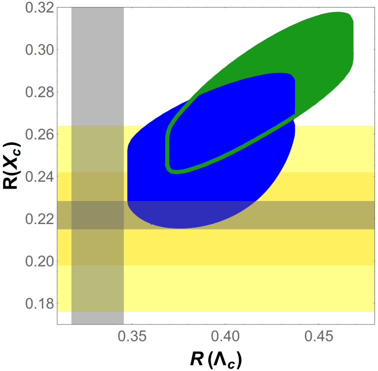
Fit predictions for $B \to X_c\tau\nu$ and $\Lambda_b \to \Lambda_c\tau\nu$:



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

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

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

➥ Data consistent with SM as well as sizable NP

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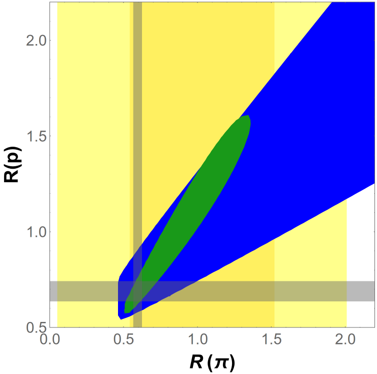
Analyse $b \to u\tau\nu$ individually:

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



More observables needed!
Λ_b provides uncommon parameter combinations
$B_s \to K^{(*)}\tau\nu$ decays competitive? Detector requirements?
Pionic final states possible?

Conclusions

Excellent physics potential for LHCb beyond Run 4

- Present tensions:
  V_{xb} exclusive vs. inclusive: progress possible/probable
  $b \to c\tau\nu$: indications of lepton-non-universal NP
  - New measurements/observables constrain NP more severely
- Any BR measurement at the (few-)% level requires dealing with production asymmetries @ B factories properly
- Should tensions be real, they're established by LS 3
  - Expect smaller deviations anyway (smaller $R(D^*)$ would improve most NP interpretations)
  - Need to pin down precise strucure of NP (Dirac, flavour)
  - Clean observables available to differentiate between different NP
  - Need for distributions + polarization measurements
- Chance to constrain $b \to u$ transitions like $b \to c$ now
  - Experimentally challenging, which detector changes could help?

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Thank you for your attention!

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!

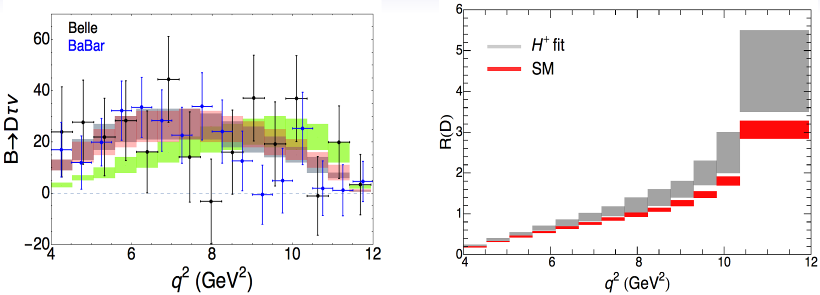
- No problem in $b \to c\tau\nu$ since $B_c \to \tau\nu$ won't be measured
- Large charm coupling required for $R(D^*)$
- ➥ Embedding $b \to c\tau\nu$ into a viable model complicated!
- ➥ $D_{d,s} \to \tau, \mu\nu$ kill typical flavour structures with $C_{S_{L,R}} \sim m$
- ➥ Only fine-tuned models survive 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 $R(D^*)$!

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 $dR(D)/dq^2$
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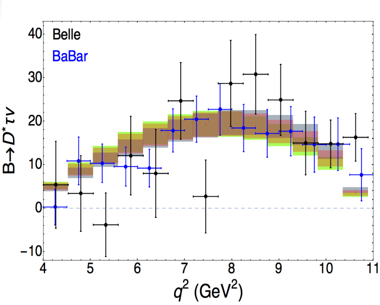

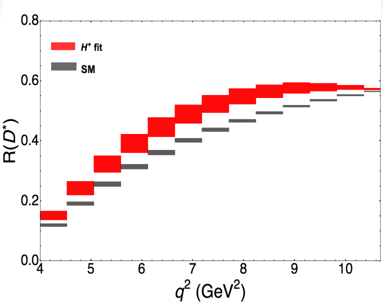

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- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D^*)$
  Red: SM fit (distributions only)
  Green: Allowed by $R(D^*)$, excluded by distribution
- Need better experimental precision, ideally $dR(D^*)/dq^2$
- Not very restrictive 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	$\chi^2_{\min}$	# 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	$\lvert g_{V_L}\rvert = 1.10$