New physics in $b \to c\ell\nu$ decays

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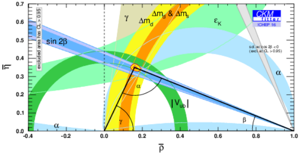
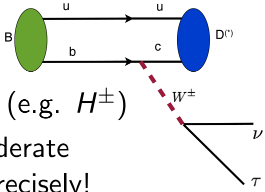
Importance of (semi-)leptonic hadron decays



In the Standard Model:

- Tree-level, $\sim |V_{ij}|^2 G_F^2 \, \mathrm{FF}^2$
- 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 small/moderate
  - ↳ Need to understand the SM very precisely!

Key advantages:

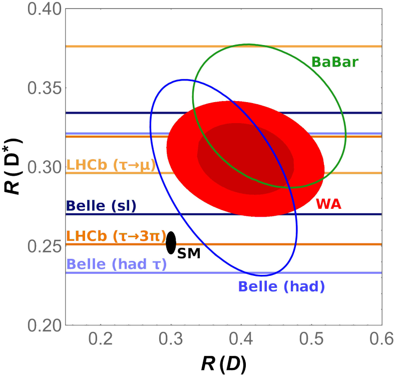
- Large rates
- Minimal hadronic input ⇒ systamatically improvable
- Differential distributions ⇒ large set of observables

Analysis mandatory due to $\tau - e/\mu$ and $e - \mu$ LFNU data

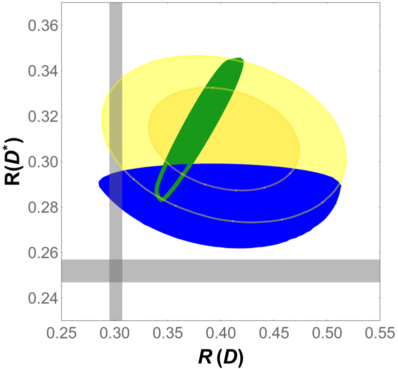
Lepton-non-Universality in $b \to c\tau\nu$ 2018

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

- $R(D^{(*)})$ 2× LHCb, 4× Belle recently
- τ-polarization ($\tau \to$ had) [1608.06391]
- $B_c \to J/\psi\tau\nu$ [1711.05623] : huge
- Differential rates from Belle, BaBar
- Total width of B_c
- $b \to X_c\tau\nu$ by LEP



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



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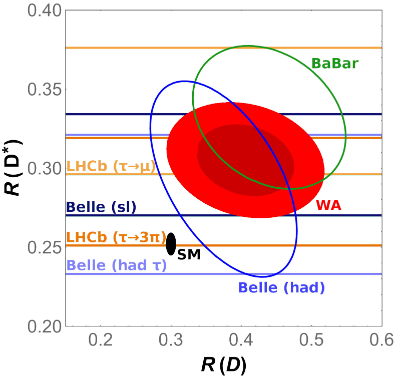

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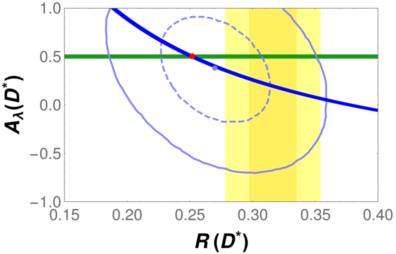
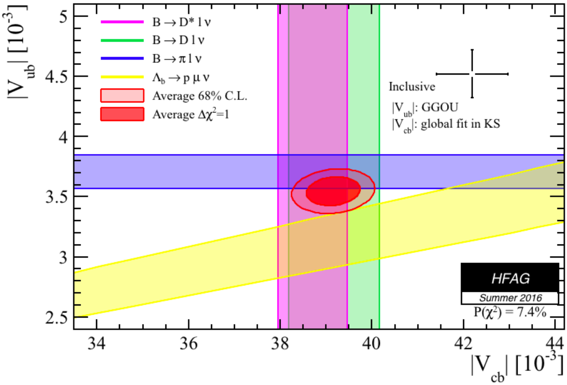


[Celis/MJ/Li/Pich'17]

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

Long-standing problem, motivation for NP [e.g. Voloshin'97] :



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

➥ Suspicion: experimental/theoretical systematics?

$|V_{cb}|$: Recent developments

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

Recent lattice results for $B \to D$

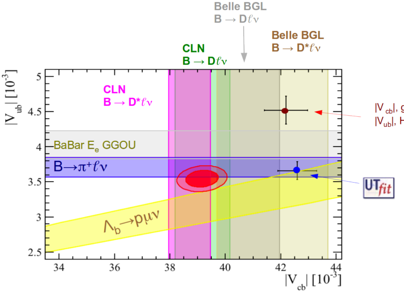
[FNAL/MILC, HPQCD, RBC/UKQCD (ongoing)]

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

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

➥ V_{cb}^{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 modification by M. Rotondo]

Theoretical uncertainties previously underestimated, in two ways:

- $1/m_c^2$ contributions likely underestimated in CLN
- Uncertainty given in CLN ignored in experimental analyses

➥ Inclusive-exclusive tension softened

Experimental analyses used

Decay	Observable	Experiment	Comment	Year
$\boldsymbol{B \to D(e,\mu)\nu}$	BR	BaBar	global fit	2008
$B \to D\ell\nu$	$\frac{d\Gamma}{dw}$	BaBar	hadronic tag	2009
$\boldsymbol{B \to D(e,\mu)\nu}$	$\frac{d\Gamma}{dw}$	Belle	hadronic tag	2015
$\boldsymbol{B \to D^*(e,\mu)\nu}$	BR	BaBar	global fit	2008
$B \to D^*\ell\nu$	BR	BaBar	hadronic tag	2007
$B \to D^*\ell\nu$	BR	BaBar	untagged B^0	2007
$B \to D^*\ell\nu$	BR	BaBar	untagged $B^\pm$	2007
$\boldsymbol{B \to D^*(e,\mu)\nu}$	$\frac{d\Gamma_{L,T}}{dw}$	Belle	untagged	2010
$B \to D^*\ell\nu$	$\frac{d\Gamma}{d(w,\cos\theta_V,\cos\theta_l,\phi)}$	Belle	hadronic tag	2017

Different categories of data:

- Only total rates vs. differential distributions
- e,μ-averaged vs. individual measurements
- Correlation matrices given or not

➥ Sometimes presentation prevents use in non-universal scenarios ☹

➥ Recent Belle analyses (mostly) exemplary ☺

Comments regarding systematics and fitting [MJ/Straub'18]

Present (and future!) precision renders small effects important:

- Form factor parametrization
- d'Agostini effect:
  assuming systematic uncertainties ~ (exp. cv) introduces bias
  ➥ e.g. 1-2σ shift in $|V_{cb}|$ in Belle 2010 binned data
- Rounding in a fit with strong correlations and many bins:
  ➥ 1σ between fit to Belle 2017 data from paper vs. HEPdata
- BR measurements and isospin violation [MJ 1510.03423] :
  Normalization depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
  Taken into account, but simple HFLAV average problematic:
  - Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
  - Measurements in $r_{+0}^{\rm HFAG}$ assume isospin in exclusive decays
    ➥ This is one thing we want to test!

  ➥ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
  (potentially subject to change, in contact with Belle members)

  ➥ Relevant for **all** BR measurements at the %-level

Form Factors

Only $V_{cb} \times \mathrm{FF}(q^2)$ extracted from data

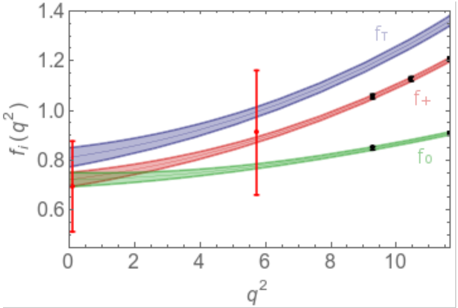
SM: fit to data + normalization from lattice/LCSR/… $\to |V_{cb}|$

NP: can affect the q^2-dependence, introduces additional FFs

➥ To determine general NP, FF shapes needed from theory

We use all available theory input:

- Unitarity bounds (using results from [BGL,Bigi/Gambino(/Schacht)'16'17])
- LQCD for $f_{+,0}(q^2)$ $(B \to D)$, $h_{A_1}(q^2_{\max})$ $(B \to D^*)$ [HPQCD'15,'17,Fermilab/MILC'14,'15]
- LCSR for $R_{1,2}(0), h_{A_1}(w = w_{\max}, 1.3), G(w = w_{\max}, 1.3)$ [Faller+'08]
- HQET relations up to $\mathcal{O}(\alpha_s, 1/m_{b,c})$ plus $1/m^2_{c,b}$ subset, mostly à la [Bernlocher+'17] , but w/o CLN relation between slope and curvature



NP in semileptonic decays - Setup and tree-level scenarios

EFT for $b \to c \ell \nu_{\ell'}$ transitions (no light ν_R, SM: $C_j^{\ell\ell'} = 0$):

$$\mathcal{L}_{\rm eff}^{b\to c\ell\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j^5 \sum_{\ell=e,\mu} \sum_{\ell'=e,\mu,\tau} \left[\delta_{\ell\ell'}\delta_{jV_L} + C_j^{\ell\ell'}\right] \mathcal{O}_j^{\ell\ell'} \,, \qquad \text{with}$$

$$\mathcal{O}_{V_{L,R}}^{\ell\ell'} = (\bar{c}\gamma^\mu P_{L,R} b)\bar{\ell}\gamma_\mu \nu_{\ell'} \,,\ \mathcal{O}_{S_{L,R}}^{\ell\ell'} = (\bar{c} P_{L,R} b)\bar{\ell}\nu_{\ell'} \,,\ \mathcal{O}_{T}^{\ell\ell'} = (\bar{c}\sigma^{\mu\nu} P_L b)\bar{\ell}\sigma_{\mu\nu}\nu_{\ell'} \,.$$

NP models typically generate subsets (never C_T alone)

- Full classification possible for tree-level mediators [Freytsis+'15] :

Model	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T	$C_{S_L} = 4C_T$	$C_{S_L} = -4C_T$
Vector-like singlet	×						
Vector-like doublet		×					
W'	×						
$H^\pm$			×	×			
S_1	×						×
R_2						×	
S_3	×						
U_1	×		×				
V_2			×				
U_3	×						

SM and left-handed vector operators

As a crosscheck, produce SM values (using data from HEPdata):

$V_{cb}^{B\to D} = (39.6 \pm 0.9)10^{-3}$ $V_{cb}^{B\to D^*} = (39.0 \pm 0.7)10^{-3}$

➥ low compared to BGL analyses, compatible with recent results

NP in $\mathcal{O}_{V_L}^{\ell\ell'}$: can be absorbed via $\tilde{V}_{cb}^{\ell} = V_{cb}\left[|1+C_{V_L}^{\ell}|^2+\sum_{\ell'\neq\ell}|C_{V_L}^{\ell\ell'}|^2\right]^{1/2}$

Only subset of data usable

$B \to D, D^*$ in agreement

No sign of LFNU

➥ constrained to be $\lesssim$ % $\times$ V_{cb}

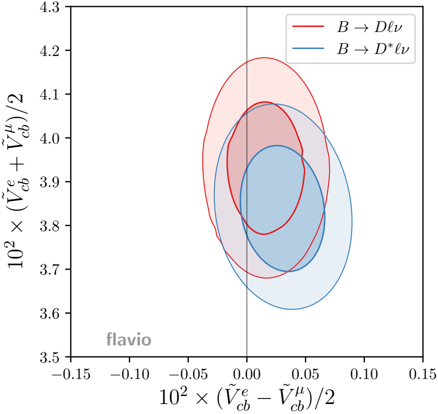
In the following:

- e and μ analyzed separately
- ➥ Usable in different contexts
- Full FF constraints used

Plots created with **flavio**

+ independently double-checked

➥ Open source, adaptable

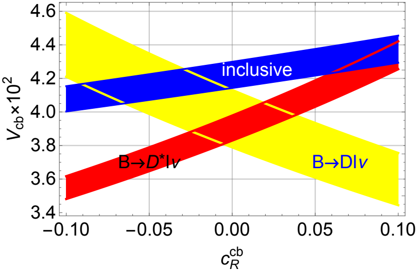


Right-handed vector currents

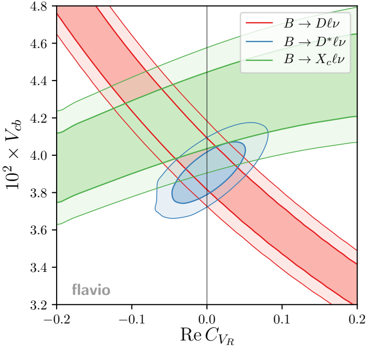
Usual suspect for tension inclusive vs. exclusive [e.g. Voloshin'97]

SMEFT: $C_{V_R}^{\ell\ell'}$ is lepton-flavour-universal [Cirigliano+'10,Catà/MJ'15]

- All available data can be used in SMEFT context
- Violation could signal non-linear realization of EWSB [Catà/MJ'15]



[Plot: updated from Crivellin/Pokorski'14]



Impact of differential distributions:

V_{cb} and C_{V_R} can be determined individually in $B \to D^*$

- Tension smaller, no improvement from C_{V_R}

Scalar operators

For $m_\ell \to 0$, no interference with SM

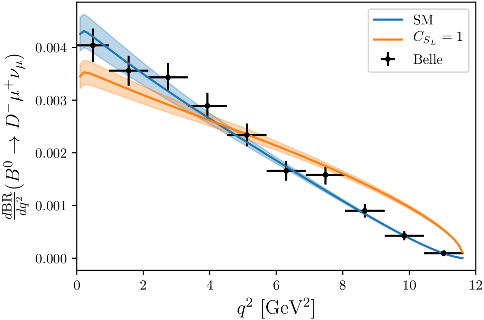
- For fixed V_{cb}, scalar NP increases rates

Close to $q^2 \to q^2_{\max}$ in the SM: $\frac{d\Gamma(B\to D\ell\nu)}{dq^2} \propto f_+^2 \left(q^2 - q^2_{\max}\right)^{3/2}$

With scalar contributions: $\frac{d\Gamma(B\to D\ell\nu)}{dq^2} \propto f_0^2 |C_{S_R} + C_{S_L}|^2 \left(q^2 - q^2_{\max}\right)^{1/2}$

- Endpoint very sensitive to scalar contributions! [see also Nierste+'08]

Scalar contributions ruled out by the distributions ($\Gamma_1 = \Gamma_2$):



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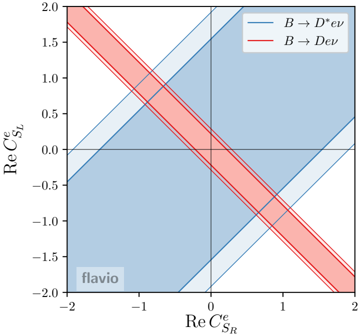
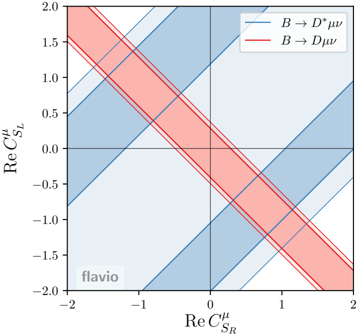
Fit with scalar couplings (generic $C_{S_{L,R}}$):





Slightly favours large contributions in muon couplings with $C^\mu_{S_R} \approx -C^\mu_{S_L}$

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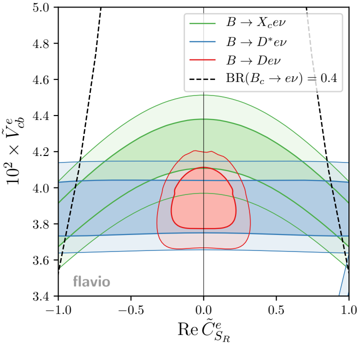
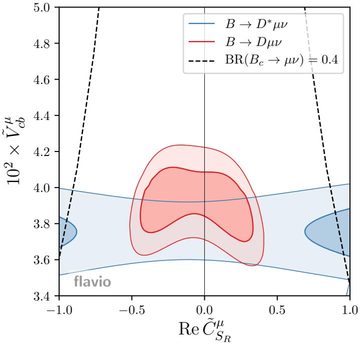
Also for LQ U_1 (or V_2): $B \to D$ stronger than $B \to D^*, X_c$:





Possible large contribution in $C^\mu_{S_R}$ excluded by $B \to D$

Tensor operators

For $m_\ell \to 0$, no interference with SM

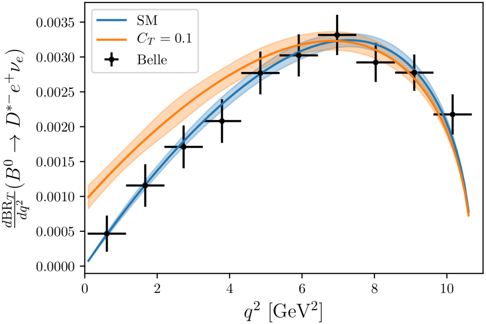
- For fixed V_{cb}, tensor contributions increase rates

Close to $q^2 \to q^2_{\rm min}$:

$$\frac{d\Gamma_T(B\to D^*\ell\nu)}{dq^2} \propto q^2\, C_{V_L}^2 \left(A_1(0)^2 + V(0)^2\right) + 16 m_B^2\, C_T^2\, T_1(0)^2 + O\left(\frac{m_{D^*}^2}{m_B^2}\right)$$

- Endpoint ($q^2 \sim 0$) very sensitive to tensor contributions!

Tensor contributions ruled out by the distributions ($\Gamma_1 = \Gamma_2$):



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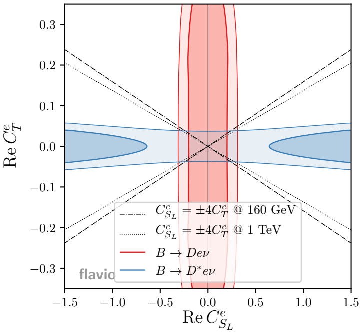
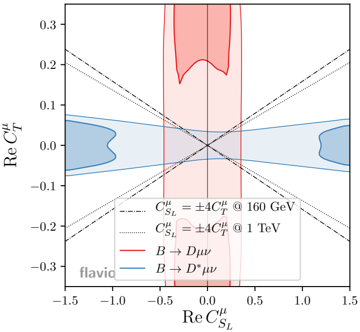
Fit for generic C_{S_L} and C_T (including LQs S_1 and R_1):





$B \to D^*$ favours large contributions in $C^{e,\mu}_{S_L}$, ruled out by $B \to D$

Conclusions

- Absence of clear NP signals → new challenges
- V_{cb} inclusive vs. exclusive softened
- New issues in determining systematic/theory uncertainties
- Form factors: so far only $f_{+,0}(q^2)$ available from LQCD
  - presently HQET relations necessary
- $b \to c\tau\nu$ and $b \to s\ell\ell$ motivate NP also in $b \to c\ell\nu$
  - Analysis requires separation of lepton flavours + correlations
- NP analysis: all scenarios with (single) tree-level mediators analyzed
  - Strong constraints on LFNU in C_{V_L}
  - Differential $B \to D^*$: new constraint on right-handed currents
  - Endpoint relations for scalars and tensors improve constraints

$b \to c\ell\nu$ beyond V_{cb}: strong NP analyzers

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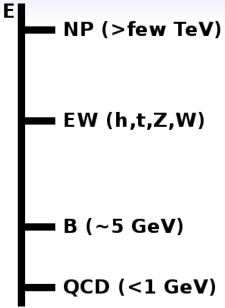
$b \to c\ell\nu$ beyond V_{cb}: strong NP analyzers

Thank you for your attention!

Higgs EFT(s)

EFT approach at the electroweak scale:

- ✓ SM particle content
- ✓ SM gauge group
- ? Embedding of h
- ? Power-counting
- ➥ Formulate NLO



E

NP (>few TeV)

EW (h,t,Z,W)

B (~5 GeV)

QCD (<1 GeV)

Linear embedding of h:

- h part of doublet H
- Appropriate for weakly-coupled NP
- Power-counting: dimensions
  - ➥ Finite powers of fields
- LO: SM

Non-linear embedding of h:

- h singlet, U Goldstones
- Appropriate for strongly- coupled NP
- Power-counting: loops ($\sim\chi$PT)
  - ➥ Arbitrary powers of $h/v, \phi$
- LO: SM $+$ modified Higgs-sector

LO and NLO in linear and non-linear HEFT

Linear EFT

Building blocks $\psi_f, X_{\mu\nu}, D_\mu, H$

Finite powers of fields

H-interactions symmetry-restricted

LO:

- Terms of dimension 4

➥ SM (renormalizable)

NLO:

- 59 ops. (w/o flavour)

[Buchmüller+'86,Grzadkowski+'10]

Non-linear EFT

Building blocks $\psi_f, X_{\mu\nu}, D_\mu, U, h$ $(U = \exp(2i\Phi/v))$

Arbitrary powers of Φ, h: $U, f(h/v)$

U-interactions symmetry-restricted

LO:

- Tree-level h,U interactions $+\ SU(2)_{L+R}$, g_{X-h} weak

➥ SM $+\ f_i(h/v)$, non-renorm.

NLO:

- ~ 100 ops. (w/o flavour)

[Buchalla+'14]

- Non-linear EFT generalizes linear EFT
- LO EFT predictive, justification for κ framework

Flavour EFTs for semi-leptonic decays

At scales $\mu \ll v$: remove top + heavy gauge bosons
- Construct EFT from light fermions + QCD, QED
- Gauge group: $SU(3)_C \times U(1)_{\rm em}$

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

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

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

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

Generically:

1. All coefficients independent
2. Coefficients for other processes unrelated (e.g. $\tau \leftrightarrow e, \mu$)

Tree-level matching of HEFT(s) on flavour-EFT

Implications of HEFT for the flavour-EFTs? [Cata/MJ'15]
Differences between linear and non-linear realization?
➥ Separate "generic" operators from non-linear HEFT

Two types of contributions:

1. Operators already present at the EW scale → identification
2. Tree-level contributions of HEFT operators with SM ones
   - ➥ *e.g.* HEFT $\bar{b}sZ$ vertex with $Z \to \ell\ell$

➥ Both of the same order

Previous work (linear EFT) e.g. [D'Ambrosio+'02,Cirigliano+'09,Alsonso+'14]

A word of caution: flavour hierarchies have to be considered!
➥ Mostly relevant when SM is highly suppressed, *e.g.* for EDMs

Implications of the Higgs EFT for flavour [Cata/MJ'15]

$\mathbf{q \to q'\ell\ell}$:

- Tensor operators absent in linear EFT for $d \to d'\ell\ell$ [Alonso+'14]
  - ➥ Present in general! (already in linear EFT for $u \to u'\ell\ell$)
- Scalar operators: linear EFT $C_S^{(d)} = -C_P^{(d)}$, $C_S'^{(d)} = C_P'^{(d)}$ [Alonso+'14]
  - ➥ Analogous for $u \to u'\ell\ell$, but no relations in general!

$\mathbf{q \to q'\ell\nu}$:

- 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

Flavour physics sensitive to Higgs embedding!
➥ Surprising, since no Higgs is involved
➥ Difficult differently [e.g. Barr+, Azatov+'15]

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 $\hat{C}_R = -\frac{1}{2}\hat{c}_{Y4}$.

BR measurements and isospin violation [MJ 1510.03423]

Detail due to high precision and small NP

➡ Relevant for $\sigma_{\mathrm{BR}}/\mathrm{BR} \sim \mathcal{O}(\%)$

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

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: assumes $f_u \equiv f_d$, uses $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$

Both approaches problematic:

- 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 $r_{+0} = 1.035 \pm 0.038$
(potentially subject to change, in contact with Belle members)