SM predictions and NP in semileptonic $b \rightarrow c$ transitions

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Importance of (semi-)leptonic hadron decays

In the Standard Model:
- Tree-level, $\sim |V_{ij}|^2 G_F^2 F F^2$
- 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!
    - For instance isospin breaking in $\Upsilon(4S) \rightarrow B\bar{B}$ [MJ’15]

Key advantages:
- Large rates
- Minimal hadronic input $\Rightarrow$ systematically improvable
- Differential distributions $\Rightarrow$ large set of observables
Lepton-non-Universality in $b \to c \tau \nu$ 2019

$$R(X) \equiv \frac{\text{Br}(B \to X\tau\nu)}{\text{Br}(B \to X\ell\nu)}, \quad \hat{R}(X) \equiv \frac{R(X)}{R(X)_{|_{SM}}}$$

- $R(D^*)$: BaBar, Belle, LHCb
  - average $\sim 4\sigma$ from SM
- $\tau$-polarization ($\tau \to \text{had}$) [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
- $D^*$ polarization (Belle)
- New@Moriond: Belle update
  - Reduced significance (partly $B \to D^*\ell\nu$)

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

Note: only 1 result $\geq 3\sigma$ from SM
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Generalities regarding this anomaly

\[ \sim 15\% \text{ of a SM tree decay } \sim V_{cb} : \text{ This is a huge effect!} \]

- Need contribution of \( \sim 5 - 10\% \) (w/ interference)
- or \( \gtrsim 40\% \) (w/o interference) of SM

What do we do about this?

- **Check the SM prediction!**
  
  \[ \rightarrow \text{Bigi}+, \text{Gambino}+, \text{Grinstein}+, \text{Bernlochner}+ \]
  
  \( \delta R(D^*) \) larger, anomaly remains

- **Combined analysis** of all \( b \rightarrow c\tau\nu \) observables [100+ papers]
  
  First model discrimination

- Related indirect bounds (partly model-dependent)
  
  High \( p_T \) searches, lepton decays, LFV, EDMs, . . .

- Analyze **flavour structure** of potential NP contributions
  
  - quark flavour structure, e.g. \( b \rightarrow u \)
  - lepton flavour structure, e.g. \( b \rightarrow c\ell (= e, \mu)\nu \)
**$R(D^*)$ from data + lattice + unitarity** [Gambino/MJ/Schacht’19]

(see also [Fajfer+, Nierste+, Bernlochner+, Bigi+, Grinstein+, Nandi+...])

Recent untagged analysis by Belle with 4 1D distributions [1809.03290]

**“Tension with the ($V_{cb}$) value from the inclusive approach remains”**

Analysis of 2017+2018 Belle data with BGL form factors:

- Datasets roughly compatible
- d’Agostini bias important
- All FFs to $z^2$ to include uncertainties
- 2018: no parametrization dependence

$$R(D^*) = 0.254^{+0.007}_{-0.006}$$
Theory determination of $b \rightarrow c$ Form Factors

SM: BGL fit to data + FF normalization $\rightarrow |V_{cb}|$

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

$\downarrow$ To determine general NP, FF shapes needed from theory

In [MJ/Straub'18, Bordone/MJ/vDyk'19], we use all available theory input:

- Unitarity bounds (using results from [BGL,Bigi/Gambino(/Schacht)'16'17])
- LQCD for $f_+,0(q^2) (B \rightarrow D), h_{A_1}(q^2_{\text{max}}) (B \rightarrow D^*)$
  [HPQCD'15,'17,Fermilab/MILC'14,'15]
- LCSR for all FFs [Gubernari/Kokulu/vDyk'18]
- Consistent HQET expansion [Bernlocher+] to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c)$
  $\downarrow$ improved description

FFs under control; $R(D^*) = 0.247(6)$
[Bordone/MJ/vDyk'19]
Robustness of the HQE expansion up to $1/m_C^2$

[Bordone/MJ/vDyk’19]

Testing FFs by comparing to data and fits in BGL parametrization:

- Fits 3/2/1 and 2/1/0 are theory-only fits(!)
- $k/l/m$ denotes orders in $z$ at $O(1, 1/m_c, 1/m_c^2)$
- $w$-distribution yields information on FF shape $→ V_{cb}$
- Angular distributions more strongly constrained by theory, only
  - Predicted shapes perfectly confirmed by $B → D(*)\ell\nu$ data
  - $V_{cb}$ from Belle’17 compatible between HQE and BGL!
Robustness of the HQE expansion up to $1/m_c^2$

[Bordone/MJ/vDyk’19]

Testing FFs by comparing to data and fits in BGL parametrization:

- $B \to D^*$ BGL coefficient ratios from:
  1. Data (Belle’17+’18) + weak unitarity (yellow)
  2. HQE theory fit 2/1/0 (red)
  3. HQE theory fit 3/2/1 (blue)

- Again compatibility of theory with data
- 2/1/0 underestimates the uncertainties massively
- For $b_i, c_i (\rightarrow f, F_1)$ data and theory complementary
Lepton-flavour structure: $\mathcal{O}_{V_L}$ [MJ/Straub'18]

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

$V_{cb}^{B \to D} = (39.6 \pm 0.9) \times 10^{-3}$ \hspace{1cm} $V_{cb}^{B \to D^*} = (39.0 \pm 0.7) \times 10^{-3}$

low compared to BGL analyses, compatible with recent results

NP in $\mathcal{O}^{\ell\ell'}_{V_L}$: 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 $\mu$ analyzed separately
- Usable in different contexts
- Full FF constraints used
- Plots created with flavio
- Independently double-checked
- Open source, adaptable
Right-handed vector currents [MJ/Straub’18]

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

SMEFT: $C_{VR}^{\ell \ell'}$ 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]

Impact of differential distributions:

- $V_{cb}$ and $C_{VR}$ can be determined individually in $B \rightarrow D^*$
- Tension smaller, but is not improved by $C_{VR}$
- $C_{VR}$ in SMEFT cannot explain $b \rightarrow c\tau\nu$ data

[Plot: updated from Crivellin/Pokorski’14]
$b \rightarrow c\tau\nu$ data and scalar NP [Celis/MJ/Li/Pich'17]

$R(D), R(D^*)$: trivially explainable, but strange

- $R(D)$: $\delta_{cb}^l \equiv \frac{(C_{SL}+C_{SR})(m_B-m_D)^2}{m_l(m_b-m_c)}$, $R(D^*)$: $\Delta_{cb}^l \equiv \frac{(C_{SL}-C_{SR})m_B^2}{m_l(m_b+m_c)}$
- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge ($|C_{SL} - C_{SR}| \sim 1 - 5$)
- 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]
$b \rightarrow c\tau\nu$ data and scalar NP \cite{Celis/MJ/Li/Pich'17}

**Total width of $B_c$:**

- $B_c \rightarrow \tau\nu$ is an obvious $b \rightarrow c\tau\nu$ transition
  - not measurable in foreseeable future
  - can oversaturate total width of $B_c$! \cite{X.Li+'16}

- Excludes second real solution in $\Delta^\tau_{cb}$ plane
  (even scalar NP for $R(D^*)$? \cite{Alonso+'16, Akeroyd+'17})
$b \rightarrow c\tau\nu$ data and scalar NP \[Celis/MJ/Li/Pich'17\]

$\tau$ polarization:

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

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

Explanation in 2HDMs possible w/ tension, flavour structure?
Differentiating models with $b \rightarrow c\tau\nu$ observables

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

- $C_{VL}$: trivial prediction: $\hat{R}(D) = \hat{R}(D^*) = \hat{R}(\Lambda_c) = \ldots \exp 1.15$
  - can be related to anomaly in $B \rightarrow K(\ast)\ell^+\ell^-$ modes
- $C_T - C_{SL}$ from scalar leptoquark
  - Requires imaginary part in couplings

Fit results for one-mediator scenarios for $B \rightarrow D(\ast)\tau\nu$:

- All coefficients complex
- (Outer) ellipses @ 95% CL
- SM prediction
- data
- only $C_{VL}$
- $C_{VL}$ and $C_{SR}$
- $C_{SL}$ and $C_{SR}$
- $C_T = +4C_{SL}$ @1 TeV
- $C_T = -4C_{SL}$ @1 TeV and $C_{VL}$
Differentiating models with $b \rightarrow c_{\tau\nu}$ observables

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

- $C_{V_L}$: trivial prediction: $\hat{R}(D) = \hat{R}(D^*) = \hat{R}(\Lambda_c) = \ldots \exp \sim 1.15$
  - can be related to anomaly in $B \rightarrow K^{(*)}\ell^+\ell^-$ modes
- $C_T - C_{S_L}$ from scalar leptoquark
  - Requires imaginary part in couplings

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

- All coefficients complex
- (Outer) ellipses @ 95% CL
- SM prediction
- data
- only $C_{V_L}$
- $C_{V_L}$ and $C_{S_R}$
- $C_{S_L}$ and $C_{S_R}$
- $C_T = +4C_{S_L}$ @1 TeV
- $C_T = -4C_{S_L}@1$ TeV and $C_{V_L}$
Differentiating models with $b \to c \tau \nu$ observables

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

- $C_{VL}$: trivial prediction: $\hat{R}(D) = \hat{R}(D^*) = \hat{R}(\Lambda_c) = \ldots \exp \sim 1.15$
  
  - can be related to anomaly in $B \to K^{(*)} \ell^+ \ell^-$ modes

- $C_T - C_{SL}$ from scalar leptoquark
  
  - Requires imaginary part in couplings

Fit predictions for additional $B \to D \tau \nu$ observables:

- All coefficients complex

- (Outer) ellipses @ 95% CL

- SM prediction

- data

- only $C_{VL}$

- $C_{VL}$ and $C_{SR}$

- $C_{SL}$ and $C_{SR}$

- $C_T = +4 C_{SL} \@ 1$ TeV

- $C_T = -4 C_{SL} \@ 1$ TeV and $C_{VL}$
Global fit to $b \rightarrow c\tau\nu$ | [Murgui/Peñuelas/MJ/Pich'19]

Analyzing $b \rightarrow c\tau\nu$ in SMEFT, w/o NP in $b \rightarrow c\ell\nu$

- $C_{VR}$ flavour universal, 4 coefficients left
- Encompasses a large class of models

Questions that can be answered in such a fit:

- Which classes of solutions exist?
- Which correlations exist for the general framework
  - Outside this, NP explanations have to be very specific
- Incompatibilities might indicate systematic issues in the data

Some observations:

- With $R(D^{(*)})$, $d\Gamma/dq^2(B \rightarrow D^{(*)}\tau\nu)$ and $\Gamma(B_c)$ three minima
  - 3rd highly disfavoured by distributions, removed by $F_L(D^*)$
- No clear preference for a specific Wilson coefficient
- Limit from $\Gamma(B_c)$ typically saturated
- Central value of $F_L$ cannot be accommodated
  - Experimental confirmation would have large impact!
Global fit to $b \rightarrow c \tau \nu$ [Murgui/Peñuelas/MJ/Pich’19]

Global minimum: requires either $C_{V_L}$ or $C_T$

- Leptoquarks provide good realizations

Local minimum: several non-zero WCs

- cannot be realized with a single mediator

Allowing for non-universal $C_{V_R}$:

- Reduces $\chi^2$, $F_L$ better fitted
- However: highly fine-tuned
  - SM almost cancelled
  - Large cancellations among NP

Again differentiation with additional observables possible
Quark flavour structure: NP in $b \rightarrow u\tau\nu$ transitions

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

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

Data consistent with SM as well as sizable NP
Quark flavour structure: NP in $b \to u\tau\nu$ transitions

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

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- $R(\pi)$ not significantly measured yet
  - Data consistent with SM as well as sizable NP

Analyse $b \to u\tau\nu$ individually:
- $R(\tau)$ yields correlation between $R(\pi)$ and $R(p)$

More observables needed!
- Requires huge data sets
- $\Lambda_b$: new parameter combinations
- $B_s \to K^{(*)}\tau\nu$ decays competitive?
  - Complementarity LHCb + Belle II
  - Possible @ CMS?
Cascade of EFTs:

Example: $R_2$ LQ

Tree-level: semileptonic operators

1-loop (matching + running):
Dipole operators are generated

Below $\mu_{EW}$: gluonic operators added

$\mu_{low} \sim 1$ GeV: → hadronic operators

- enter EDM calculations
- MEs have large uncertainties
Phenomenological consequences

Most observables constrain (mainly) real parts
- EDMs constrain complementarily \textit{imaginary} parts

Flavour-dependence of constraints
- Vastly different magnitudes
- Most relevant observables differ
- Complementarity of measurements!

![Graphs showing constraints on X_{eu}, X_{ec}, X_{et}, X_{mu}, X_{mc}, X_{mu}, X_{tau}, and X_{tau}c with different colors and markers.](image)
Relation to $R(D) - R(D^*)$ flavour anomaly

$R_2$ LQ part of NP model for flavour anomalies: [Bečirević+’18]

- Generates $C_{SL} \sim 4C_T \left( \@\mu_{LQ} \right)$
- Explanation of $R(D^{(*)})$ possible, but requires imaginary part
- The same coupling combination yields $(\bar{c}\sigma^{\mu\nu}\gamma_5 c)(\bar{\tau}\sigma_{\mu\nu}\tau)$
  - Generates charm (+ $\tau$) EDMs + Weinberg operator
  - Bounds from neutron + Hg EDMs

2 effects:

1. Weinberg operator: smaller effect (outer line)
2. Charm EDM: depends on charm tensor-current neutron ME 1 calculation [Alexandrou+’17]
   - compatible with 0

Future EDM experiments or lattice can improve this
Conclusions

Indications of LFNU in $b \to c\tau \nu$ transitions remain exciting

- Form factors: theory determinations for NP required
  - First analysis at $1/m_c^2$ provides all FFs
  - $V_{cb}$ puzzle almost gone, $R(D^*)$ slightly lower

- $b \to c\ell \nu$: strong constraints, qualitative progress for $V_R$

- $b \to c\tau \nu$: Model differentiation possible w/ additional observables
  - e.g. $B_c \leftrightarrow R(D^*)$ for $S_{L,R}$, $\hat{R}$ for $V_L$

- Scalar LQs: possible solution with implied CPV ($\to$ EDMs)

- $b \to u$ requires high-luminosity experiments

- General SMEFT analysis: $F_L$ potentially important observable

- Specific models challenged by more indirect constraints
  - e.g. high-$p_T$ observables

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Exciting times ahead in semileptonic decays!
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 $\sim (\exp. \ cv)$ introduces bias
  e.g. 1-2$\sigma$ shift in $|V_{cb}|$ in Belle 2010 binned data
- Rounding in a fit with strong correlations and many bins:
  $1\sigma$ between fit to Belle 2017 data from paper vs. HEPdata
- BR measurements and isospin violation [MJ 1510.03423]:
  Normalization depends on $\Upsilon \rightarrow B^+B^-$ vs. $B^0\bar{B}^0$
  Taken into account, but simple HFLAV average problematic:
    - Potential large isospin violation in $\Upsilon \rightarrow BB$ [Atwood/Marciano’90]
    - Measurements in $r_{10}^{\text{HFAG}}$ 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
Claim in 2018 [Chavez-Saab/Toledo]: \( R(D_\pi) \sim 0.275 \), “Closing the gap” . . .

\[ \text{This was wrong, erratum: 0.253 (in line w/ others)} \]

Erratum due to numerical issue; here: conceptual issue

The amplitudes for the decay chain are written as

\[
\begin{align*}
\langle D^*(k, \eta) | \bar{c} \gamma^\mu (1 - \gamma_5) b | \bar{B}(k + q) \rangle & \equiv \eta^*_\alpha(k) \mathcal{M}^{\mu\alpha} \\
\langle D_\pi | \mathcal{L}_{QCD} | D^*(k, \eta) \rangle & = \eta^\prime_\alpha(k) \mathcal{M}^{\alpha^\prime}
\end{align*}
\]

- \( \mathcal{M}^{\mu\alpha} \) is then parametrized in a standard way by FFs
- The polarization sum in narrow width approximation yields

\[
\sum_{\lambda=\pm1,0} \eta(\lambda) \eta^*_\alpha(\lambda) = - \left( g_{\alpha\alpha'} - \frac{k_{\alpha} k_{\alpha'}}{M_{D^*}^2} \right)
\]

\[ \text{For } k_{\alpha} k^{\alpha} = M_{D^*}^2, \text{ a contribution } \sim k^{\alpha} \text{ in } \mathcal{M}^{\alpha\mu} \text{ vanishes!} \]
Allowing for a propagating off-shell $D^*$:
Additional terms have to be suppressed by $\Gamma_{D^*/|k_{D^*}|}$!

Why does that not happen in [Chavez-Saab/Toledo’18]?

- $M^\alpha\mu$ has to fulfill on-shell-condition $k_\alpha M^\alpha\mu = 0$ for on-shell $D^*$!
- The standard FF parametrization does not fulfill this
  - Usually irrelevant due to the narrow-width approximation
  - Off-shell $D^*$: $k_\alpha M^\alpha\mu = 0$ must be ensured modifying FFs

\[ q^\mu \rightarrow q^\mu - \frac{(q \cdot k)}{k^2} k^\mu, \]

\[ g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \rightarrow g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} - \frac{k^\mu k^\nu}{k^2} + \frac{(q \cdot k) k^\mu q^\nu}{k^2 q^2}. \]

Result: expected suppression of off-shell contributions
- Tiny, can be safely neglected
BR measurements and isospin violation [MJ 1510.03423]

Detail due to high precision and small NP

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

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 $r_{+0}^{\text{HFAG}} = 1.058 \pm 0.024$

Both approaches problematic:

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in $r_{+0}^{\text{HFAG}}$ 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)
Higgs EFT(s) - relating cc and nc processes

Apparent gap between EW and NP scales:
- EFT approach at the electroweak scale:
  - SM particle content
  - SM gauge group
  - Embedding of $h$
  - Power-counting
  - Formulate NLO

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 ($\sim \chi_{\text{PT}}$)
  - Arbitrary powers of $h/v, \phi$
- LO: SM + modified Higgs-sector
Implications of the Higgs EFT for flavour EFT [Cata/MJ’15]

At scales $\mu \ll \mu_{EW}$: remove top + heavy gauge bosons

- Construct EFT from “light” fermions + QCD, QED
- Gauge group: $SU(3)_C \times U(1)_{em}$

Example: $b \rightarrow c\tau\nu$ transitions:

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

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

- All operators 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 absent in the non-linear EFT
- Flavour physics can distinguish between Higgs embeddings!
Two types of contributions:

1. Operators already present at the EW scale $\rightarrow$ identification

2. Tree-level contributions of HEFT operators with SM ones
   - e.g. HEFT $\bar{b}sZ$ vertex with $Z \rightarrow \ell\ell$

   Both of the same order

Previous work (linear EFT) e.g. [D’Ambrosio+’02,Cirigliano+’09,Alonso+’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 \cite{Cata/MJ'15}

**$q \rightarrow q'\ell\ell$ :**

- Tensor operators absent in linear EFT for $d \rightarrow d'\ell\ell$ \cite{Alonso+'14}  
  ➳ Present in general! (already in linear EFT for $u \rightarrow u'\ell\ell$)

- Scalar operators: linear EFT $C_S^{(d)} = -C_P^{(d)}$, $C_S'^{(d)} = C_P'^{(d)}$ \cite{Alonso+'14}  
  ➳ Analogous for $u \rightarrow u'\ell\ell$, but no relations in general!

**$q \rightarrow q'\ell\nu$ :**

- 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.  
  $$\sum_{U=u,c,t} \lambda_U s \, C_S^{(U)} = -\frac{e^2}{8\pi^2} \lambda_t s \, C_S^{(d)}$$  
  [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]
NP in semileptonic decays - Setup and tree-level scenarios

EFT for $b \rightarrow c\ell\nu_{\ell'}$ transitions (no light $\nu_R$, SM: $C_{j\ell\ell'} = 0$):

$$L_{\text{eff}}^{b\rightarrow c\ell\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_{j} \sum_{\ell,\ell'=e,\mu,\tau} \left[ \delta_{\ell\ell'}\delta_j V_L + C_{j\ell\ell'} \right] O_{j\ell\ell'},$$

with

$$O_{\ell\ell'}^{V,L,R} = (\bar{c}\gamma^\mu P_{L,R} b)\bar{\ell}\gamma^\mu \nu_{\ell'}, \quad O_{\ell\ell'}^{S,L,R} = (\bar{c}P_{L,R} b)\bar{\ell}\nu_{\ell'}, \quad O_{\ell\ell'}^{T} = (\bar{c}\sigma^{\mu\nu} P_L b)\bar{\ell}\sigma_{\mu\nu}\nu_{\ell'}.$$

NP models typically generate subsets (never $C_T$ alone)

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

<table>
<thead>
<tr>
<th>Model</th>
<th>$C_{V_L}$</th>
<th>$C_{V_R}$</th>
<th>$C_{S_R}$</th>
<th>$C_{S_L}$</th>
<th>$C_T$</th>
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<th>$C_{S_L} = -4C_T$</th>
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<td>Vector-like doublet</td>
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<tr>
<td>$W'$</td>
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<td>$S_1$</td>
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<td>$R_2$</td>
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<tr>
<td>$S_3$</td>
<td>×</td>
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<td>$U_1$</td>
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<td>$V_2$</td>
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<td>$U_3$</td>
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</table>
Implications of the Higgs EFT for Flavour: $q \rightarrow q' \ell \nu$

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

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

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

- 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.
  $$
  \sum_{U=u,c,t} \lambda_{Us} C^{(U)}_{SR}^{(d)} = -\frac{e^2}{8\pi^2} \lambda_{ts} C^{(d)}_S \quad [\text{see also Cirigliano+’12,Alonso+’15}]
  $$
- These relations are again absent in the non-linear EFT
Matching for $b \rightarrow c \ell \nu$ transitions

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

where $N_{CC} = \frac{1}{2 V_{cb} \Lambda^2}$, $C_L = 2 c_{LL2} - \hat{c}_{LL6} + \hat{c}_{LL7}$ and $\hat{C}_R = -\frac{1}{2} \hat{c}_{Y4}$. 
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 $\Phi, h$: $U, f(h/v)$

$U$-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:**
- $\sim 100$ ops. (w/o flavour)

[Buchalla+’14]

- Non-linear EFT generalizes linear EFT
- LO EFT predictive, justification for $\kappa$ framework
Experimental analyses used

<table>
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<th>Decay</th>
<th>Observable</th>
<th>Experiment</th>
<th>Comment</th>
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<td>$B \to D^*\ell\nu$</td>
<td>$\frac{d\Gamma}{d(w,\cos \theta_V,\cos \theta_L,\phi)}$</td>
<td>Belle</td>
<td>hadronic tag</td>
<td>2017</td>
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</tbody>
</table>

Different categories of data:

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

⚠️ Sometimes presentation prevents use in non-universal scenarios 😞

😊 Recent Belle analyses (mostly) exemplary 😊
Scalar operators

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

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

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

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

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

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

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

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

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

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

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

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

Slightly favours large contributions in muon couplings with $C_{SR}^\mu \approx -C_{SL}^\mu$
Scalar operators

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

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

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

With scalar contributions: \[
\frac{d\Gamma(B \to D\ell\nu)}{dq^2} \propto f_0^2 |C_{SR} + C_{SL}|^2 (q^2 - q_{\text{max}}^2)^{1/2}
\]

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

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

Possible large contribution in $C_{SR}^\mu$ excluded by $B \to D$
Tensor operators

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

**For fixed $V_{cb}$, tensor contributions increase rates**

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

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

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

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

[Graph showing $d\Gamma_T(B \rightarrow D^*\ell\nu)/dq^2$ vs. $q^2$]
Tensor operators

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

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

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

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

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

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

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