Theoretical prospects on V_{ub} and V_{cb}

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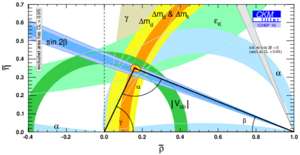
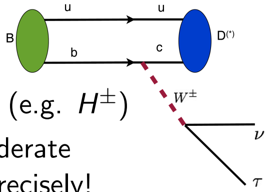
Talk at the XIII Meeting on B Physics: "Synergy between LHC and SUPERKEKB in the Quest for New Physics"
Marseille, France, 1st of October 2018

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)
  ➥ This talk



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 $\Upsilon(4S) \to B\bar{B}$ [MJ'15]

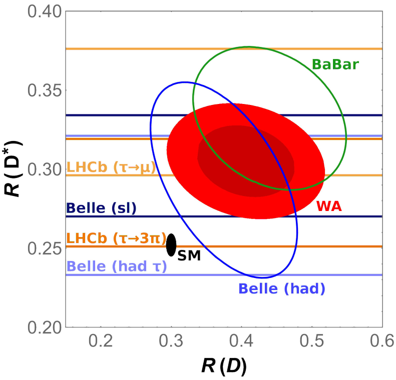
Key advantages:

- Large rates
- Minimal hadronic input $\Rightarrow$ systematically improvable
- Differential distributions $\Rightarrow$ large set of observables

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

[Talks tomorrow by D. Buttazzo + A. Morris]

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



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

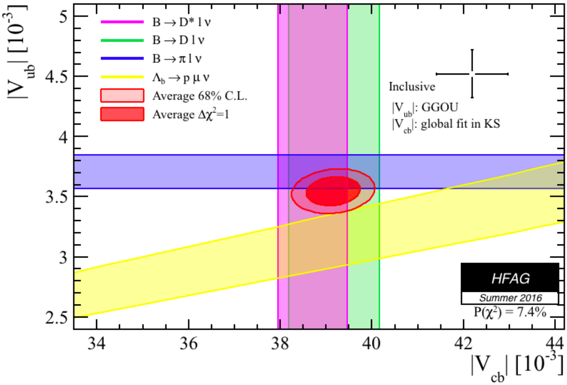
- $R(D^{(*)})$:
  2× LHCb, 4× Belle recently
  ➥ average $\sim 4\sigma$ from SM
- τ-polarization ($\tau \to$ had) [1608.06391]
- $B_c \to J/\psi\tau\nu$ [1711.05623] : huge
- Differential rates from Belle, BaBar
- Total width of B_c
- $b \to X_c\tau\nu$ by LEP
- New: $F_L(D^*)$ [Belle@CKM'18]

Present e, μ results separately!

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

Example of complementarity between LHC and SuperKEKB!

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?

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

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

- d'Agostini effect:
  assuming systematic uncertainties $\sim$ (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
- Problem: how to provide unfolded data independent from the (precise) signal hypothesis?
  ➥ Indpendent of form factor parametrization (later)
  ➥ Independent of potential NP contributions
  (more severe for $b \to c\tau\nu$)

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 $r_{+0}^{\mathrm{HFAG}} = 1.058 \pm 0.024$
  (also usually used for sl analyses by B factories)

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 $r_{+0} = 1.035 \pm 0.038$

Inclusive V_{cb} determination

Inclusive $B \to X_c \ell \nu$ calculated in operator product expansion:

- Systematic expansion in $1/m_{b,c}$ and α_s
- State of the art: [Alberti/Becher/Bigi/Biswas/Boos/Czarnecki/Ewerth/Gambino/Lunghi/Mannel/Melnikov/Nandi/Pak/Pivovarov/Rosenthal/...]
  - $\mathcal{O}(\alpha_s^0)$: parametrization up to $1/m^5$ (proliferation of hadronic parameters from $1/m^4$)
  - $\mathcal{O}(\alpha_s^1)$: up to $1/m^2$, $1/m^3$ work in progress [Gambino+]
  - $\mathcal{O}(\alpha_s^2)$: leading order
  - ➥ Consistent fit, seen e.g. in quark-mass determination

$$|V_{cb}| = (42.00 \pm 0.64) \times 10^{-3} [Gambino+' 16]$$

Prospects: [Gambino@CKM]

- α_s/m^3 underway, α_s^3 "feasible" (total rate), necessary?
- Weak+e/m effects require attention ($\to$ theory vs. experiment)
- Lattice determination of local B matrix elements [Kronfeld/Simone,Gambino/Melis/Simula]

➥ Improvements in sight, several steps to qualitative new level

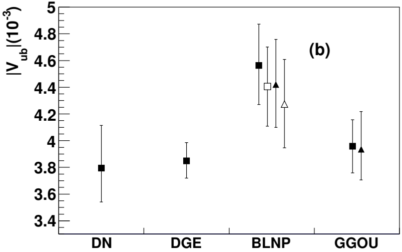
Inclusive V_{ub} determination

In a perfect world: analogous to V_{cb} inclusive.

The difference between theory and practice is that in theory, there is no difference, but in practice there is.

$|V_{ub}|^2/|V_{cb}|^2 \sim 1\%$

- Truly inclusive measurement flooded with $b \to c$ background
- Non-local OPE, hadronic functions instead of parameters
  - Leading shape function universal, extracted from $B \to X_s\gamma$
  - Subleading SF treatment: new approaches NNVub + SIMBA
  - Moments of SFs related to hadronic parameters in $B \to X_c\ell\nu$



Meanwhile...

- New BaBar analysis 2017
- High E_ℓ-region critical
- 3/4 methods: lower $|V_{ub}|$
- Effect in other studies?

Exp+Theo collaboration essential

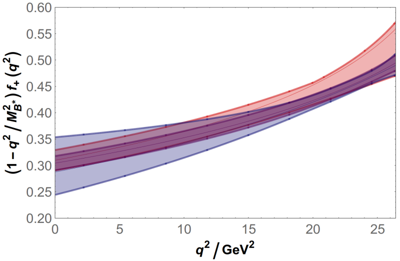
Exclusive V_{ub} determinations

Traditionally: $B \to \pi\ell\nu$, $B \to \rho$ (weaker)

- Complementarity: $B \to \pi(\rho)$ @ Belle II, new modes @ LHCb
- $|V_{ub}/V_{cb}|$ via $\Lambda_b \to p$ vs. $\Lambda_b \to \Lambda_c$, $B_s \to K^{(*)}$ vs. $B_s \to D_s$, $B_c(?)$

Larger kinematical range accessible

- combine lattice and LCSR via pseudodata / BCL coefficients



Determination over full kin. range
LCSR: NLO twist 2+3, LO higher-twist, NNLO [Khodjamirian+,Ball+,Bharucha]
Lattice: Immense recent progress!

- extending q^2 range, 2+1+1, ...

[Celis/MJ/Li/Pich'17]

$B \to \rho$: Recent LCSR results [Bharucha+'15] , issue: ρ theo/exp

- $B \to \pi\pi\ell\nu$ description [Faller+,Cheng+,Feldmann+,Kim+,Böer+,Kang+,Meißner+]

$\Lambda_b \to p$: first $|V_{ub}/V_{cb}|$ result, improvement (exp+theo) ongoing
$B_s \to K$: form factor improvements [Khodjamirian+,FNAL/MILC,RBC/UKQCD]

- Excellent prospects, a lot to gain from LHC + SuperKEK-B!

Exclusive $b \to c$ determinations

Dominated by $B \to D^{(*)}$, $B_s \to D_s^{(*)}$ possible (competitive?)
Heavy to heavy transition $\to$ HQET domain, lattice difficult

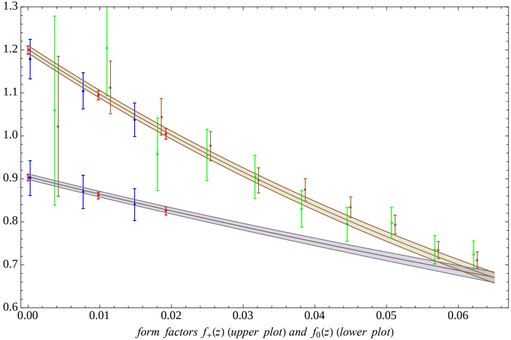
$B \to D, D^*$ form factors:

- Unitarity + analyticity used to obtain expansion in z
  - ➡ $|z| \ll 1$, used in CLN + BGL parametrization alike
  - ➡ BGL: formulation such that coefficients ≤ 1 as well
- CLN: uses heavy-quark limit to relate $B^* \to D^{(*)}$ FFs
  - ➡ Expansion in $1/m_{b,c}$ and α_s (known to NLO)
    LO: unique function [Isgur/Wise] , $1/m$ 3(4) additional functions
    $1/m^2$ structure known [Falk+] , but 1 unknown function per FF
  - ➡ extremely efficient parametrization up to $1/m$ and α_s
- Up to 2015: typically V_{cb} from CLN-parametrization fit
  - ➡ 2 problems: CLN error estimate optimistic + ignored by exp.

Recent discussion: how large are $1/m_c^2$ corrections?

V_{cb} from $B \to D$

2015: Unfolded $B \to D\ell\nu$ spectra [Belle] + finite recoil LQCD [HPQCD,MILC]



Analysis by Bigi/Gambino:

- Improved unitarity constraints
- Lattice data "contradict" CLN (sensitivity to higher $1/m$ orders)

➥ $|V_{cb}| = 40.49(96) \times 10^{-3}$, compatible with V_{cb}^{incl} and $B \to D^*$

V_{cb} from $B \to D^*$

2017: Prel. unfolded spectrum (4 variables) from Belle

- However, in this case no finite-recoil FFs available from lattice
- w/ Belle results SM fit in BGL possible (including lattice (+LCSR))

Results: [Bigi+,Grinstein+]

- Both CLN and BGL yield excellent fits
  - $|V_{cb}^{\mathrm{CLN}}| = 38.2(15) \times 10^{-3}$
  - $|V_{cb}^{\mathrm{BGL}}| = 41.7(21)[40.4(17)] \times 10^{-3}$ w/ or w/o LCSR
    - BGL $1-2\sigma$ higher, larger difference than expected!
  - Intriguing result, but requires confirmation exp. + lattice

[1809.03290]: New Belle result

- $|V_{cb}^{\mathrm{CLN}}| = 38.4(2)(6)(5)10^{-3}$ $|V_{cb}^{\mathrm{BGL}}| = 42.3(3)(7)(6)10^{-3}$

Uncertainties due to parametrization were underestimated

- Using BGL, there is no indication of a V_{cb} puzzle
- Lattice data should resolve the issue within the year

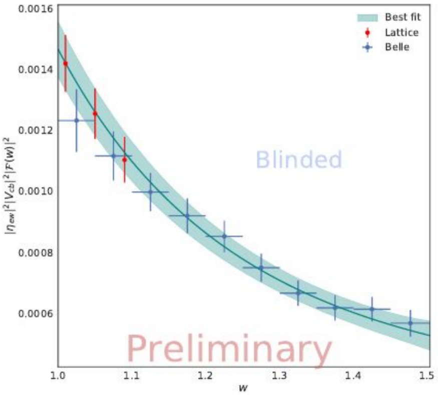
N.B.: This discussion relates to SM $R(D, D^*)$ predictions

Status lattice calculation of $B \to D^*$

Chris Monahan @ CKM:

FNAL/MILC: first (blind) 2+1 results, on MILC AsqTad ensembles

First result for R(D*) soon...



$b \to c$ Form Factors beyond the SM

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

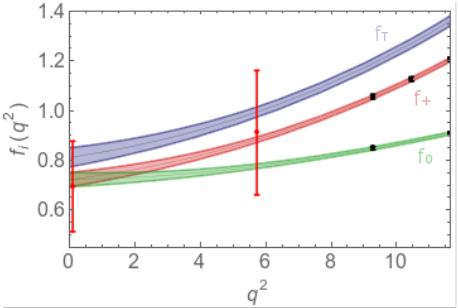
SM: fit to data + normalization from lattice/LCSR/... $\to |V_{cb}|$

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

➡ To determine general NP, FF shapes needed from theory

In [MJ/Straub'18] , 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



Conclusions

Absence of clear NP signals $\rightarrow$ new challenges

- Issues like isospin breaking now center of attention
- V_{cb}^{incl} stable and still improvable (theory homework)
- V_{ub}^{incl}: BaBar result needs to be understood
  - ➥ No resolution, but "suggestive"
- V_{ub}^{excl}: Theoretical and experimental progress in parallel
  - ➥ New modes + improved existing ones
  - ➥ expect signiificant improvement!
- V_{cb}^{excl}: $B \rightarrow D$ lattice sensitive to $1/m^2$ corrections
  - ➥ Improved $V_{cb} + R(D)$ determination w/ BGL
- $B \rightarrow D^*$ awaits first finite-recoil LQCD calculation, BGL vs. CLN

➥ V_{xb} puzzles severely reduced

- NP analyses require lattice determinations also of non-SM FFs!

THANK YOU!

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

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

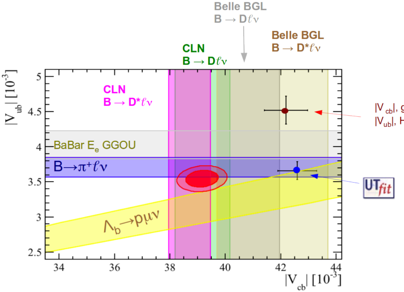
$|V_{cb}|$: Recent developments

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]
➥ $V_{cb}^{\rm incl}$ 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 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
$\mathbf{B \to D(e,\mu)\nu}$	BR	BaBar	global fit	2008
$B \to D\ell\nu$	$\frac{d\Gamma}{dw}$	BaBar	hadronic tag	2009
$\mathbf{B \to D(e,\mu)\nu}$	$\frac{d\Gamma}{dw}$	Belle	hadronic tag	2015
$\mathbf{B \to D^*(e,\mu)\nu}$	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
$\mathbf{B \to D^*(e,\mu)\nu}$	$\frac{d\Gamma_{L,T}}{dw}$	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 ☺

NP in semileptonic decays - Setup and tree-level scenarios

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

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

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

NP models typically generate subsets (never C_T alone)

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

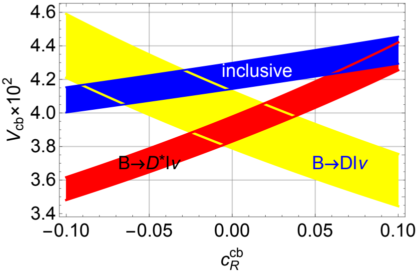
Model	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T	$C_{S_L} = 4C_T$	$C_{S_L} = -4C_T$
Vector-like singlet	×						
Vector-like doublet		×					
W'	×						
$H^\pm$			×	×			
S_1	×						×
R_2						×	
S_3	×						
U_1	×		×				
V_2			×				
U_3	×						

Right-handed vector currents [MJ/Straub'18]

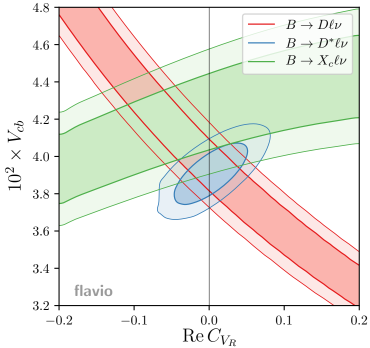
Usual suspect for tension inclusive vs. exclusive [e.g. Voloshin'97]

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]

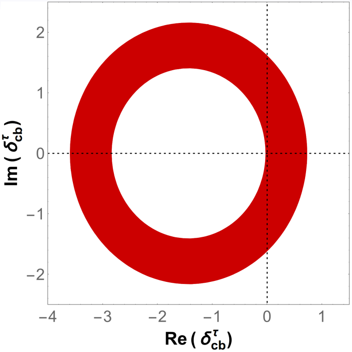


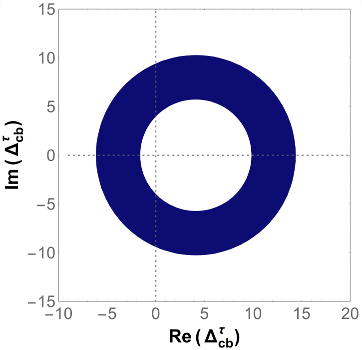
Impact of differential distributions:

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

- Tension smaller, but is not improved by C_{V_R}
- C_{V_R} in SMEFT cannot explain $b\to c\tau\nu$ data

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

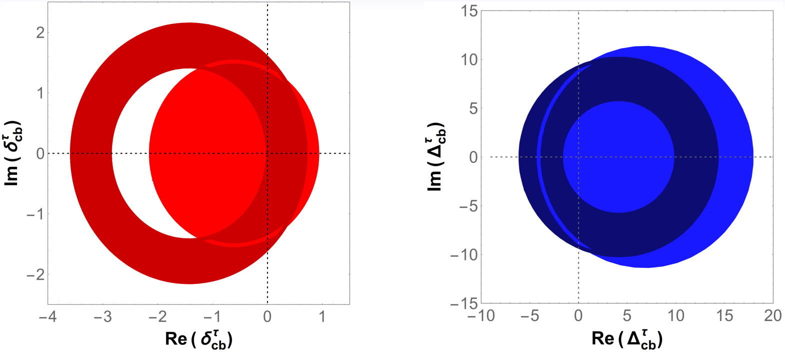




$R(D), R(D^*)$: trivially explainable, but strange

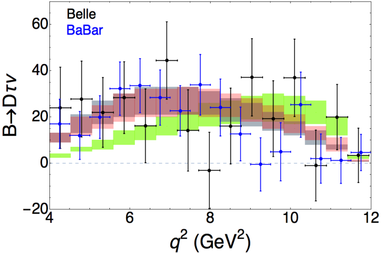
- $R(D):\ \delta^l_{cb} \equiv \frac{(C_{S_L}+C_{S_R})(m_B-m_D)^2}{m_l(\bar{m}_b-\bar{m}_c)}$, $R(D^*):\ \Delta^l_{cb} \equiv \frac{(C_{S_L}-C_{S_R})m_B^2}{m_l(\bar{m}_b+\bar{m}_c)}$
- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge $(|C_{S_L} - C_{S_R}| \sim 1-5)$
- Can't go beyond circles with just $R(D, D^*)$!

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

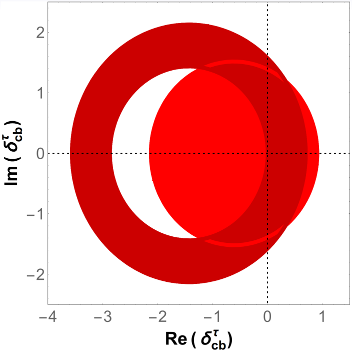


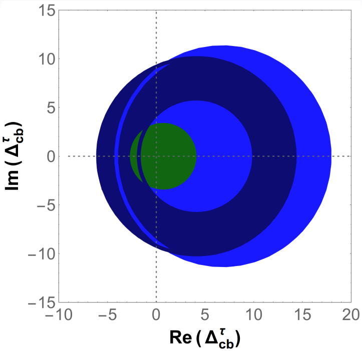
Differential rates:

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



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

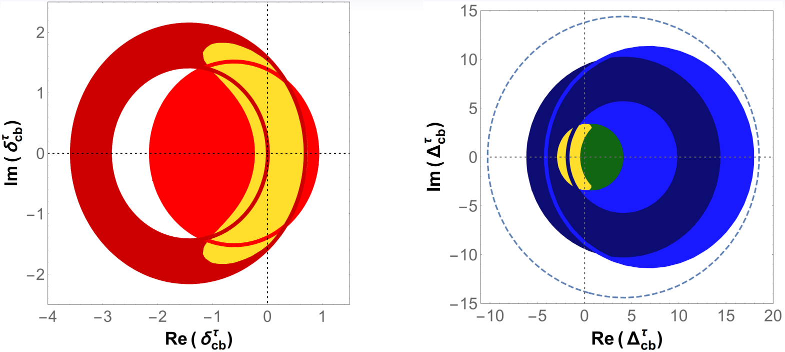




Total width of B_c:

- $B_c \to \tau\nu$ 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, Akeroyd+'17])

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



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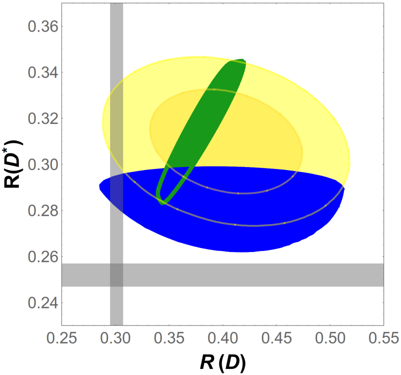
Fit results for the two scenarios for $B \to D^{(*)}\tau\nu$:



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

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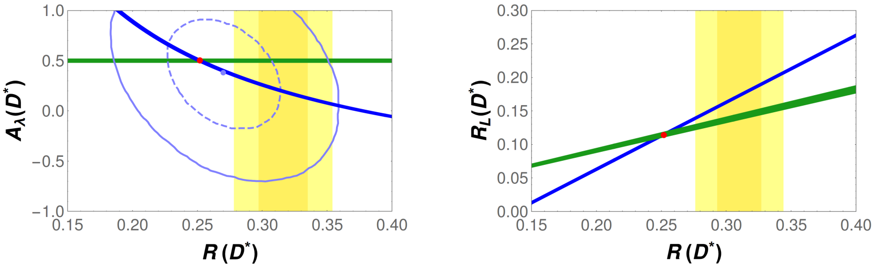
- issues with $\tau \to \mu\nu\nu$ [Feruglio+'16] and $b\bar{b} \to X \to \tau^+\tau^-$ [Faroughy+'16]

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



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

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

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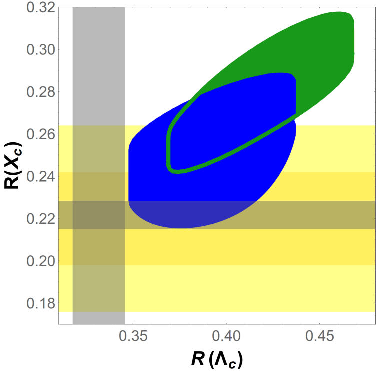
Fit predictions for $B \to X_c\tau\nu$ and $\Lambda_b \to \Lambda_c\tau\nu$:



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

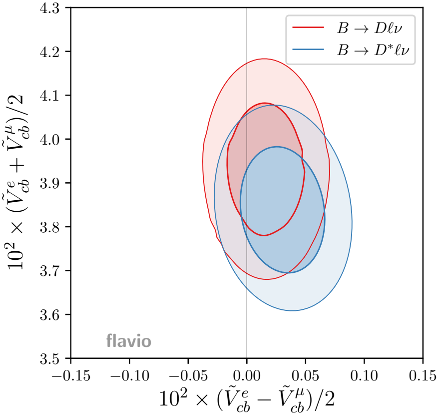
NP in $\mathcal{O}_{V_L}^{\ell\ell'}$: can be absorbed via $\tilde{V}_{cb}^{\ell} = V_{cb}\left[|1+C_{V_L}^{\ell}|^2+\sum_{\ell'\neq\ell}|C_{V_L}^{\ell\ell'}|^2\right]^{1/2}$

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



Scalar operators

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

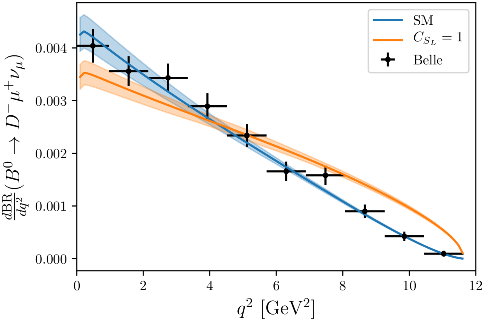
➡ For fixed V_{cb}, scalar NP increases rates

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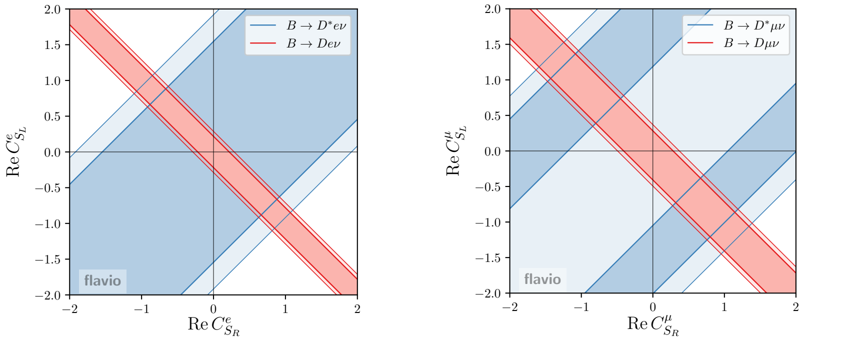
Fit with scalar couplings (generic $C_{S_{L,R}}$):



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

Scalar operators

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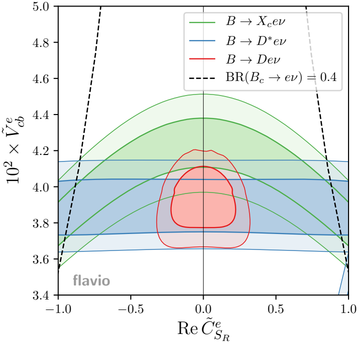
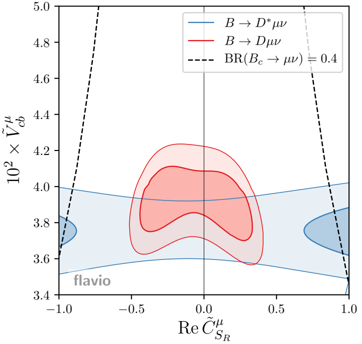
Close to $q^2 \to q^2_{\max}$ in the SM: $\frac{d\Gamma(B\to D\ell\nu)}{dq^2} \propto f_+^2 \left(q^2 - q^2_{\max}\right)^{3/2}$

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]

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

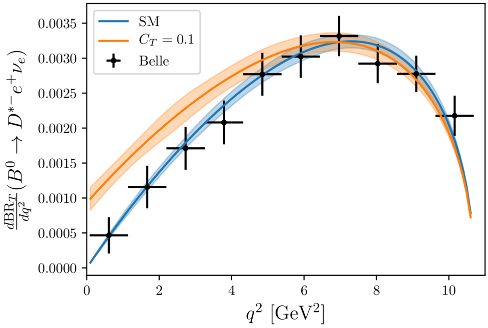
➥ For fixed V_{cb}, tensor contributions increase rates

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

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

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

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



Tensor operators

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

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

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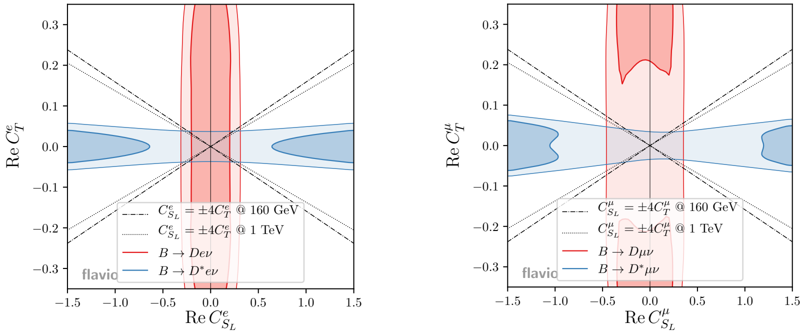
➥ Endpoint ($q^2 \sim 0$) very sensitive to tensor contributions!

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 $B \to D$