V_{cb} and form factors in $B \to D^{(*)}\ell\nu$

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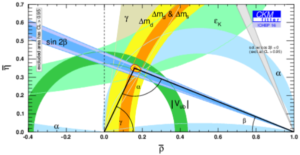
Talk at the workshop
"Implications of LHCb measurements and future prospects"
17th of October 2019

Importance of (semi-)leptonic hadron decays

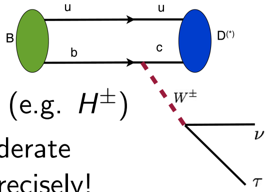
In the Standard Model:

- Tree-level, $\sim |V_{ij}|^2 G_F^2\, \mathrm{FF}^2$
- Determination of $|V_{ij}|$ (7/9)



Beyond the Standard Model:

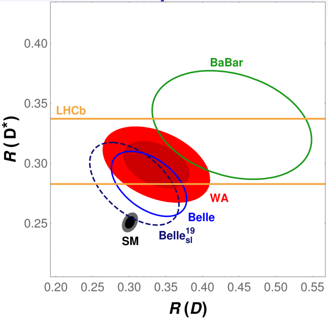
- Leptonic decays $\sim m_l^2$
  - ➥ large relative NP influence possible (e.g. $H^{\pm}$)
- NP in semi-leptonic decays small/moderate
  - ➥ Need to understand the SM very precisely!
    e.g. radiative corrections [see R. Szafron's talk]



Key advantages:

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

Lepton-non-Universality in $b \to c\tau\nu$ 2019



contours 68%, filled 95% CL

- $R(D^{(*)})$: BaBar, Belle, LHCb
  - ➥ average $3.x\sigma$ from SM
- Other $b \to c$ observables:
  - ➥ largely SM-like ($R(J/\psi)$ large even w/ NP)
- $R(K^{(*)})$: $\sim 4\sigma$ from SM
  - ➥ between light leptons
- $b \to s\ell\ell$ global fit: $\sim 5\sigma$

$\sim$ 15% of a SM tree decay $\sim V_{cb}$: This is a huge effect!
➥ Need contribution of $\sim 5-10\%$ (w/ interference) or $\gtrsim 40\%$ (w/o interference) of SM

➥ Check SM prediction (main topic of this talk)

➥ NP analyses [talks by D.Guadagnoli,O.Sumensari,Soni,M.König,A.Peñuelas]

➥ Require form factors independent of data!

Form factor parametrizations

FFs central non-perturbative input in semileptonic decays, e.g.

$$\langle D(p_D)|\bar{c}\gamma^\mu b|\bar{B}(p_B)\rangle = f_+(q^2)\left[(p_B^\mu + p_D^\mu) - \frac{M_B^2 - M_D^2}{q^2} q^\mu\right] + f_0(q^2)\frac{M_B^2 - M_D^2}{q^2} q^\mu$$

"BGL parametrization":

- Analytic structure: account for cuts and poles explicitly
  - ➥ remainder can be expanded in simple power series in z
- Use quark-hadron-duality (+crossing sym., unitarity)
  - ➥ Absolute bounds on coefficients, rapid convergence

➥ Efficient expansion of individual FFs with few coefficients

"HQE parametrization" ($\to$ CLN)

- Exploit heavy-quark spin-flavour symmetry for $m_{b,c} \to \infty$
  - ➥ All $B^{(*)} \to D^{(*)}$ FFs given by Isgur-Wise function $\xi(z)$
  - ➥ Systematic expansion in $1/m_{b,c}$ and α_s
  - ➥ Also z expansion, no bounds on individual coefficients

➥ Less parameters in total, FFs related

Puzzling V_{cb} results

The V_{cb} puzzle has been around for 20+ years...

- $\sim 3\sigma$ between exclusive (mostly $B \to D^* \ell\nu$) and inclusive V_{cb}
- Inclusive determination: includes $\mathcal{O}(1/m_b^3, \alpha_s/m_b^2, \alpha_s^2)$
  - ➡ Excellent theoretical control, $|V_{cb}| = 42.00 \pm 0.64$
- Exclusive determinations: $B \to D^{(*)}\ell\nu$, using CLN (fixed!)
  - ➡ CLN: HQE @ $\mathcal{O}(1/m_{c,b}, \alpha_s)$ + slope-curvature relation in ξ

Recent developments:

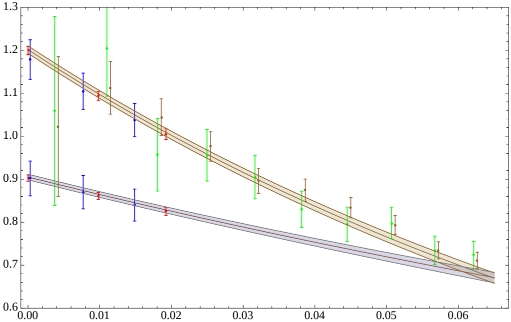
- Unfolded differential measurements made available by Belle
  - ➡ Different parametrizations possible
- Lattice calculations for $B \to D$ FFs at non-zero recoil

➡ Agreement of analyses for $B \to D$

- $B \to D^*$ FFs: several analyses ongoing [see O. Witzel's talk]
  So far: only one FF at zero recoil
  - ➡ Larger differences in theory analyses
  - ➡ Specifically treatment of $1/m_c^2$ important
- New LCSR analysis of all $B \to D^{(*)}$ FFs [Gubernari/Kokulu/vDyk'18]

V_{cb} from $B \to D$

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



form factors $f_+(z)$ (upper plot) and $f_0(z)$ (lower plot)

BGL 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 $V_{cb}^{\rm incl}$ and $B \to D^*$

HQE analysis w/ partial $1/m_c^2$ works [Bernlochner+’17,MJ/Straub’18]

V_{cb} from $B \to D^*$ 2017

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

Uncertainties due to parametrization were underestimated
- Using BGL, no indication of a V_{cb} puzzle in 2017 data
- Lattice data will give additional insights

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

$V_{cb} + R(D^*)$ w/ data + lattice + unitarity [Gambino/MJ/Schacht'19]

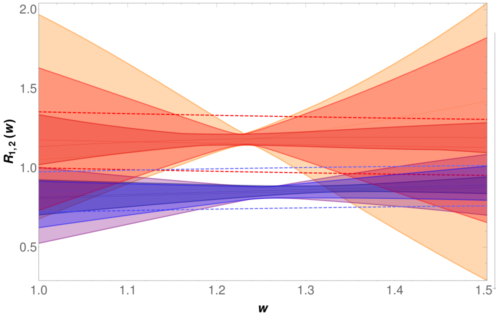
(see also [Fajfer+,Nierste+,Bernlochner+,Bigi+,Grinstein+,Nandi+. . .])
Recent untagged analysis by Belle with 4 1D distributions [1809.03290]

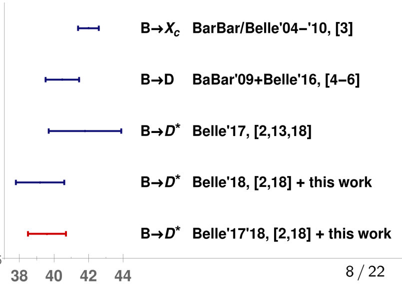
➡ *"Tension with the (V_{cb}) value from the inclusive approach remains"*

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

- Datasets roughly compatible
- d'Agostini bias + syst. important
- All FFs to z^2 to include uncertainties
- 2018: no parametrization dependence

$$|V_{cb}^{D^*}| = 39.6^{+1.1}_{-1.0} \times 10^{-3}$$
$$R(D^*) = 0.254^{+0.007}_{-0.006}$$





Theory determination of $b \to c$ Form Factors

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

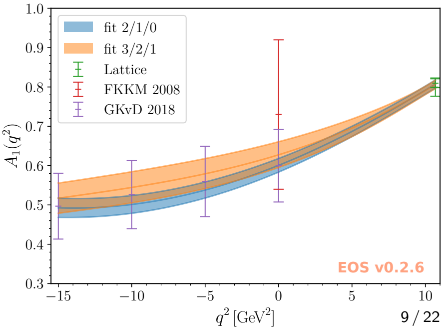
NP: can affect the q^2-dependence, introduces additional FFs

➡ To determine general NP, FF shapes needed from theory

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

- Unitarity bounds (using results from [BGL,Bigi/Gambino(/Schacht)'16'17])
- LQCD for $f_{+,0}(q^2)$ $(B \to D)$, $h_{A_1}(q^2_{\max})$ $(B \to D^*)$ [HPQCD'15,'17,Fermilab/MILC'14,'15]
- LCSR for all FFs but f_T [Gubernari/Kokulu/vDyk'18]
- Consistent HQET expansion to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$
  ➡ improved description [Bordone/MJ/vDyk'19]

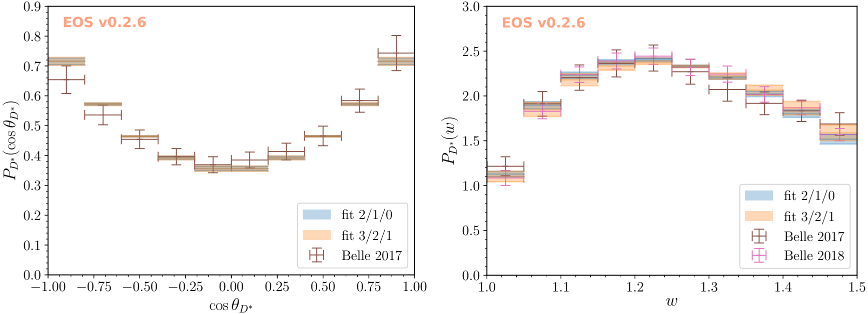
FFs under control;
$R(D^*) = 0.247(6)$
$V_{cb} = 40.0(11) \times 10^{-3}$



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 $\mathcal{O}(1, 1/m_c, 1/m_c^2)$
- w-distribution yields information on FF shape $\to V_{cb}$
- Angular distributions more strongly constrained by theory, only

➥ Predicted shapes perfectly confirmed by $B \to D^{(*)}\ell\nu$ 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]

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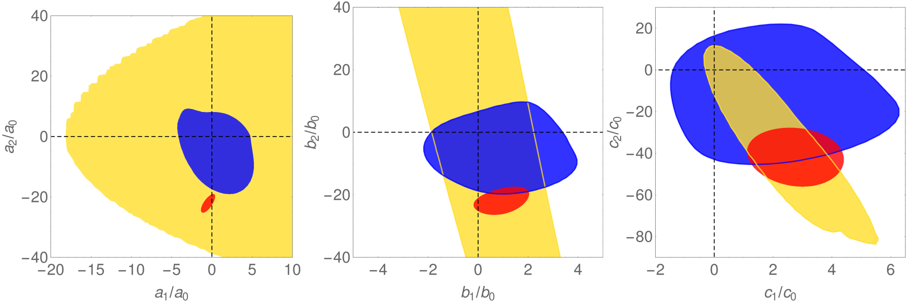


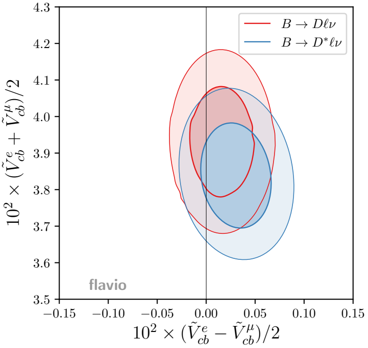
- $B \to D^*$ BGL coefficient ratios from:
  1. Data (Belle'17+'18) + weak unitarity (yellow)
  2. HQE theory fit 2/1/0 (red)
  3. HQE theory fit 3/2/1 (blue)

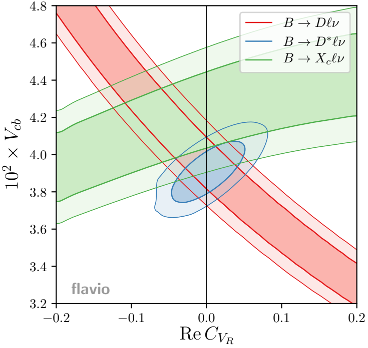
➥ Again compatibility of theory with data

➥ 2/1/0 underestimates the uncertainties massively

➥ For b_i, c_i ($\to f, \mathcal{F}_1$) data and theory complementary

An example NP analysis: $b \to c\ell\nu(\ell = e, \mu)$ [MJ/Straub'18]





NP in left-handed vector current:

$$\tilde{V}_{cb}^\ell = V_{cb}\left[|1 + C_{V_L}^\ell|^2 + \sum_{\ell' \neq \ell} |C_{V_L}^{\ell\ell'}|^2\right]^{1/2}$$

Only subset of data usable

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

No sign of LFNU

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

NP in right-handed vector current:

Usual suspect for excl. vs. incl. [e.g. Voloshin'97]

Test of SMEFT [Catá/MJ'15]

Full $B \to D^{(*)}$ data usable

$B \to D^*$: Qualitative change

No constraint over SM

Conclusions

$b \to c$ transitions important in the SM and beyond; various puzzles

- Recent developments allow for qualitatively new analyses
  - BGL analyses of $B \to D^{(*)}$ reduce V_{cb} puzzle
  - 2017+2018 data: still $V_{cb} \sim 1.9\sigma$ from $V_{cb}^{\text{incl.}}$
  - Large parametrization dependence in Belle 2017 data
- For NP theory determination of form factors required
  - First analysis at $1/m_c^2$ provides all FFs
  - Parametrization dependence in Belle data removed
  - Excellent agreement w/ data, $1/m_c$ expansion works
- Averaging $B \to (D, D^*, X_c)\ell\nu$: "Tension" at $1.x\sigma$
- NP in $b \to c\ell\nu$: strong constraints, qualitative progress for V_R

Exciting times ahead in semileptonic decays!

$B \to D\pi$ vs. $B \to D^*$ I [MJ/vDyk('19)]

Claim in 2018 [Chavez-Saab/Toledo] : $R(D\pi) \sim 0.275$, "*Closing the gap*" . . .

➡ 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

$$\langle D^*(k,\eta)|\,\bar{c}\gamma^\mu(1-\gamma_5)b\,|\bar{B}(k+q)\rangle \equiv \eta^*_\alpha(k)\mathcal{M}^{\mu\alpha}$$
$$\langle D\pi|\,\mathcal{L}_{\rm QCD}\,|D^*(k,\eta)\rangle = \eta_{\alpha'}(k)\mathcal{M}^{\alpha'}$$

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

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

➡ For $k_\alpha k^\alpha = M^2_{D^*}$, a contribution $\sim k^\alpha$ in $\mathcal{M}^{\alpha\mu}$ vanishes!

$B \to D\pi$ vs. $B \to D^*$ II [MJ/vDyk('19)]

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] ?

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

$$q^\mu \mapsto q^\mu - \frac{(q \cdot k)}{k^2} k^\mu \,,$$

$$g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \mapsto g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} - \frac{k^\mu k^\nu}{k^2} + \frac{(q \cdot k)\, k^\mu q^\nu}{k^2\, q^2} \,.$$

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 $\sigma_{\rm BR}/{\rm BR} \sim \mathcal{O}(\%)$

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

Both approaches 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!

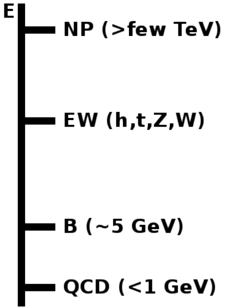
➡ Avoiding this assumption yields $r_{+0} = 1.035 \pm 0.038$
(potentially subject to change, in contact with Belle members)

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 ($\sim\chi$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: $SU(3)_C \times U(1)_{\rm em}$

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

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

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

- 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!

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 $\rightarrow$ 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 [Cata/MJ'15]

$q \to q'\ell\ell$:

- 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!

$q \to q'\ell\nu$:

- 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]

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 ☺

Scalar operators

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

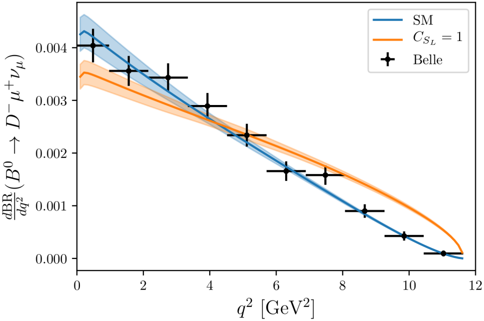
- For fixed V_{cb}, scalar NP increases rates

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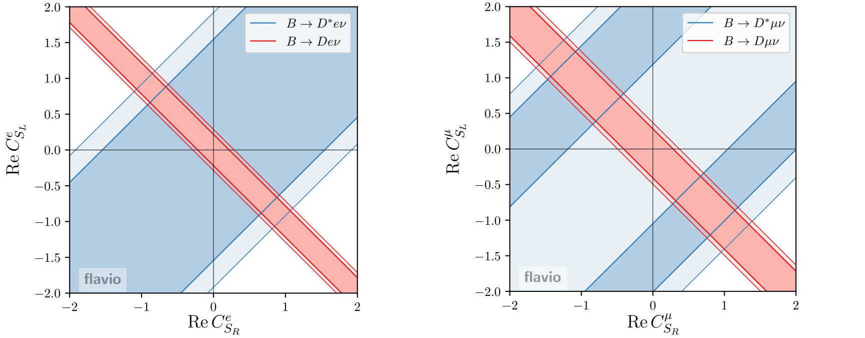
Fit with scalar couplings (generic $C_{S_{L,R}}$):



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

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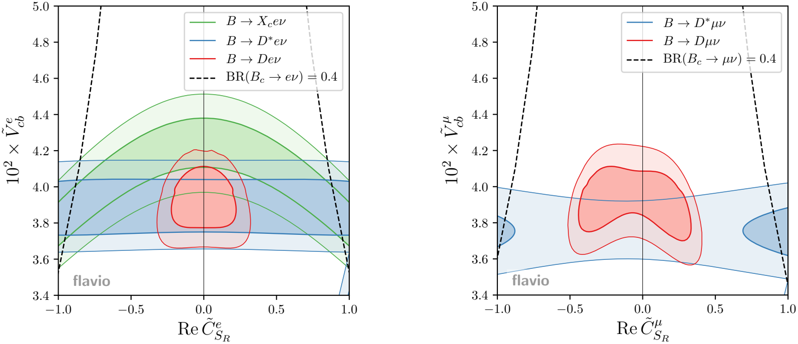
➡ Endpoint very sensitive to scalar contributions! [see also Nierste+'08]

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

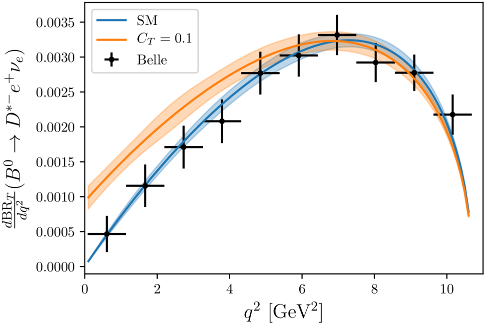
- For fixed V_{cb}, tensor contributions increase rates

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

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

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

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



Tensor operators

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

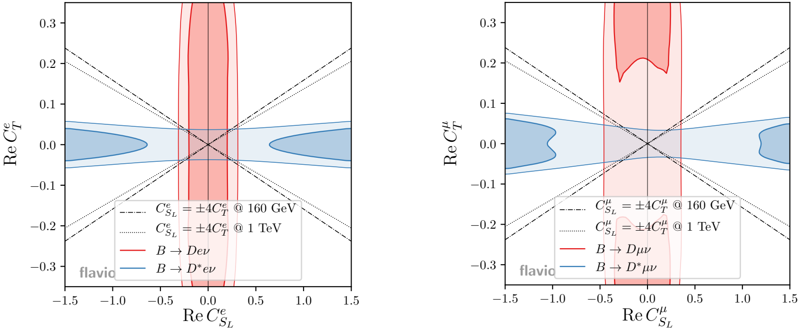
- For fixed V_{cb}, tensor contributions increase rates

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!

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 $B \to D$