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

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"New physics at the low-energy precision frontier"
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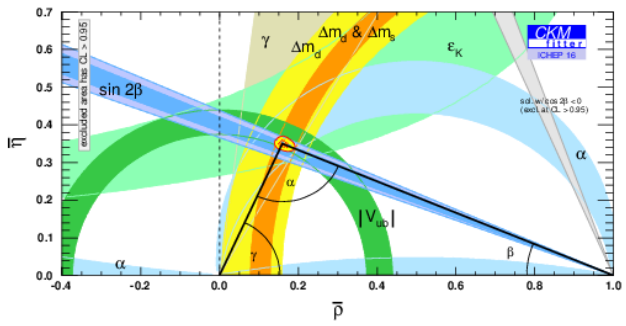
Importance of (semi-)leptonic hadron decays

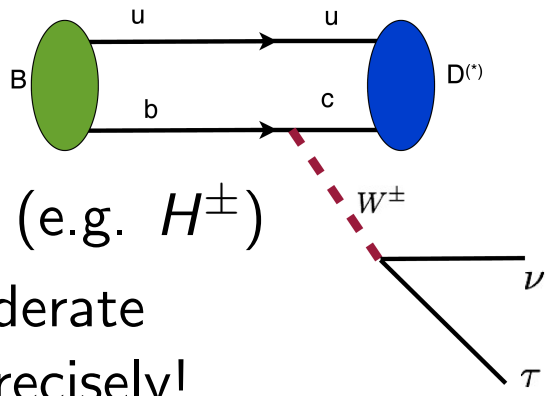
In the Standard Model:

- 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!
    For instance isospin breaking in $\Upsilon(4S) \to B\bar{B}$ [MJ'15]

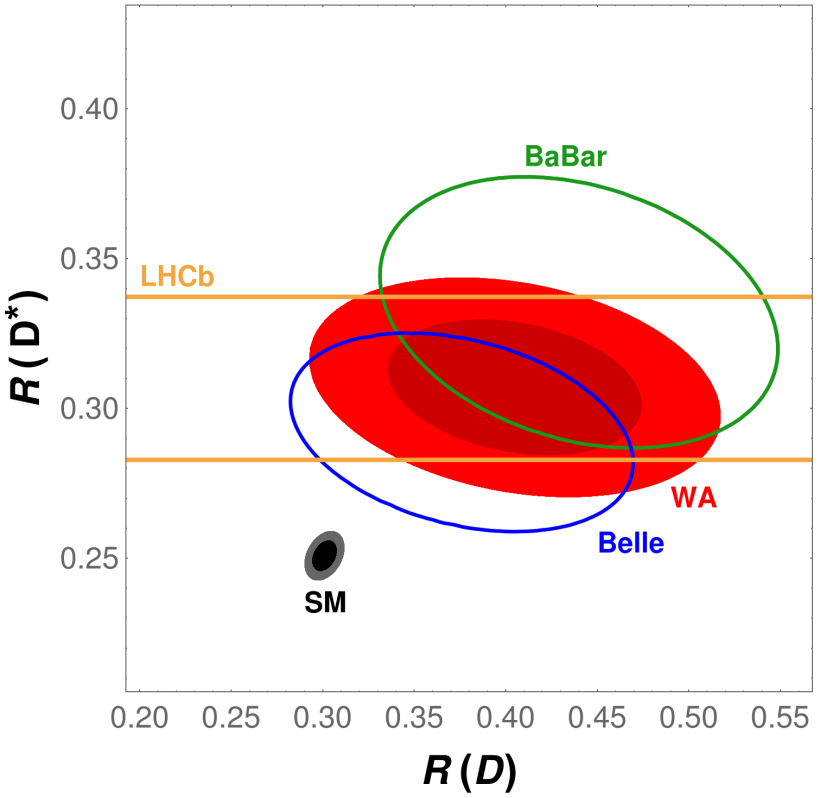


Key advantages:

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

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

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



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

- $R(D^{(*)})$: BaBar, Belle, LHCb
  - ➥ 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
- D^* polarization (Belle)
- New@Moriond: Belle update
  - ➥ Reduced significance (partly $B \to D^*\ell\nu$)

Note: only 1 result $\geq 3\sigma$ from SM

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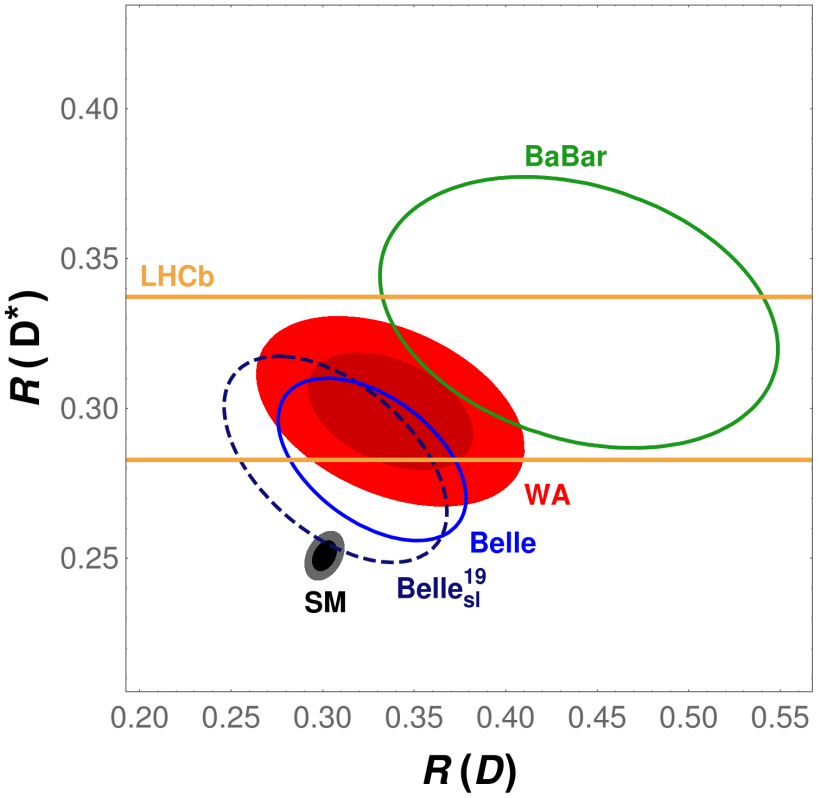

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Generalities regarding this anomaly

$\sim 15\%$ 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

What do we do about this?

- Check the SM prediction!
  [→ Bigi+,Gambino+,Grinstein+,Bernlochner+]
  ➥ $\delta R(D^*)$ larger, anomaly remains
- Combined analysis of all $b \to c\tau\nu$ 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. $b \to u$
  ➥ lepton flavour structure, e.g. $b \to c\ell(= e, \mu)\nu$

$R(D^*)$ from data + lattice + unitarity [Gambino/MJ/Schacht'19]

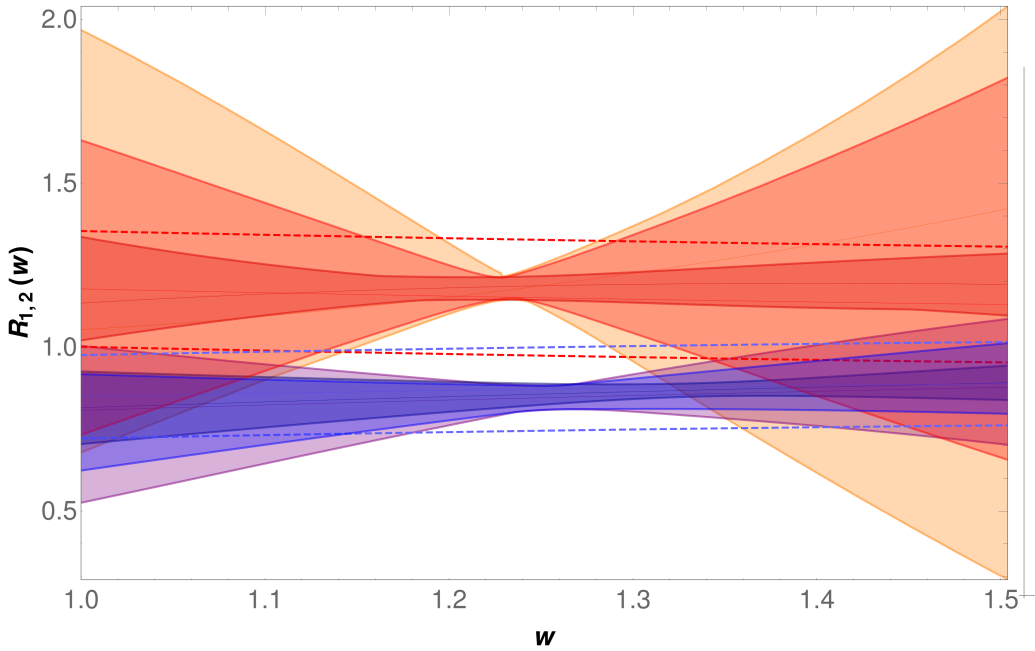
(see also [Fajfer+,Nierste+,Bernlochner+,Bigi+,Grinstein+,Nandi+...])
Recent untagged analysis by Belle with 4 1D distributions [1809.03290]

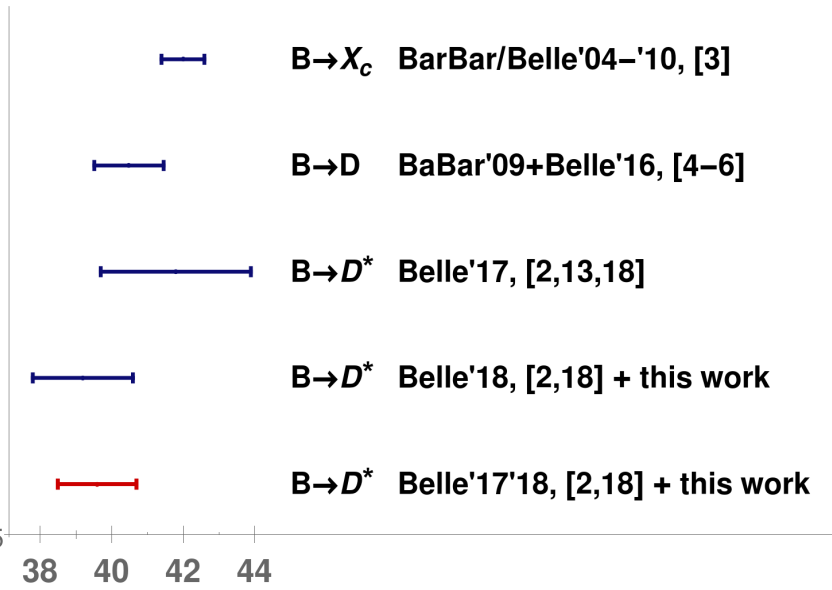
➥ *"Tension with the (V_{cb}) value from the inclusive approach remains"*

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 $b \to c$ Form Factors

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

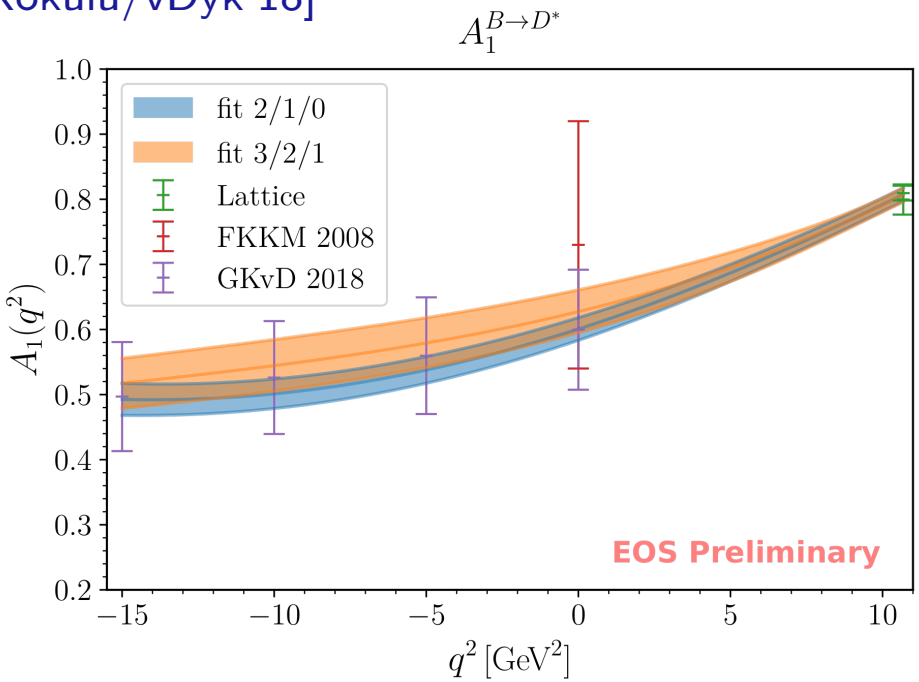
NP: can affect the q^2-dependence, introduces additional FFs

➥ 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 [Gubernari/Kokulu/vDyk'18]
- Consistent HQET expansion [Bernlocher+] to $\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2)$
  ➥ improved description

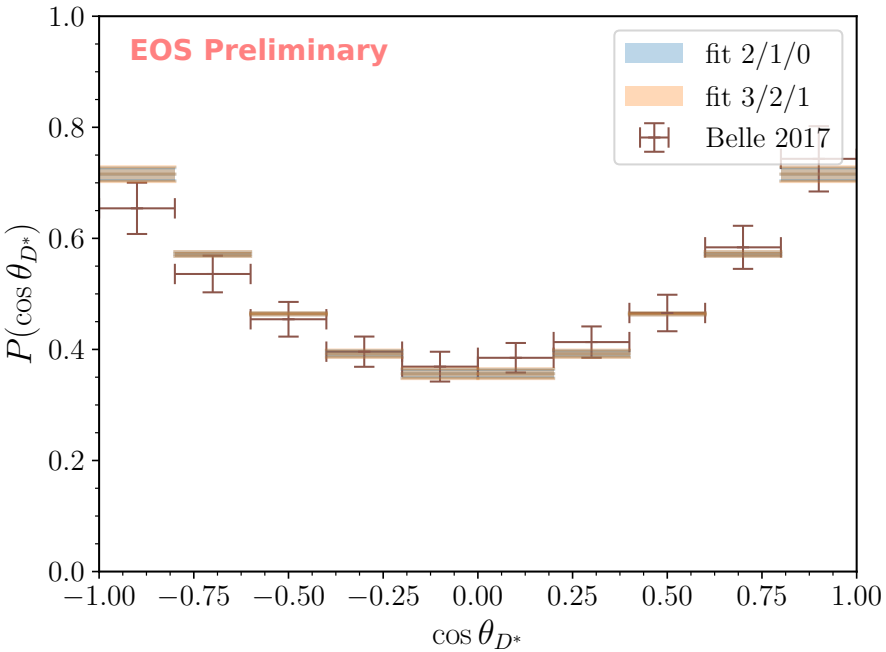
FFs under control;
$R(D^*) = 0.247(6)$
[Bordone/MJ/vDyk'19]

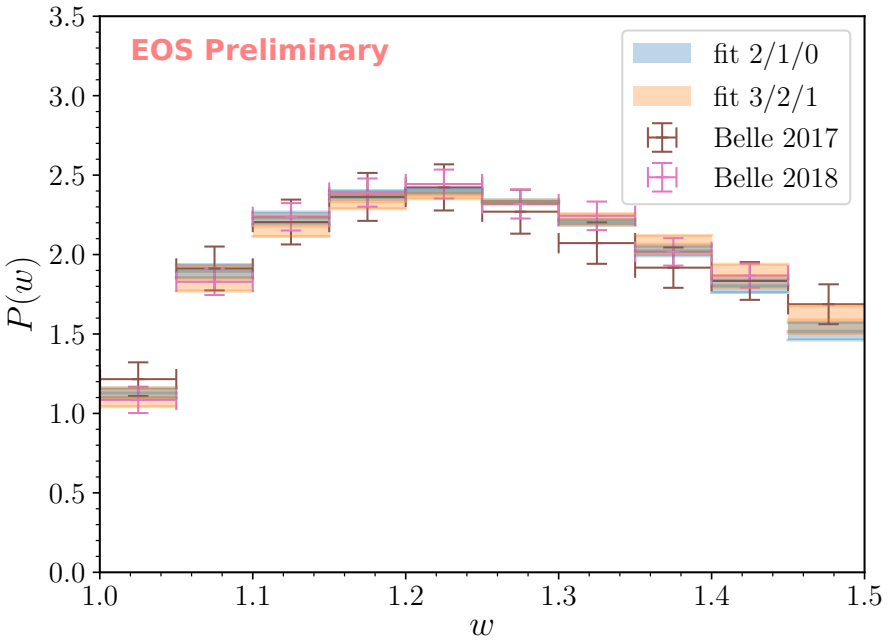


Robustness of the HQE expansion up to $1/m_c^2$

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

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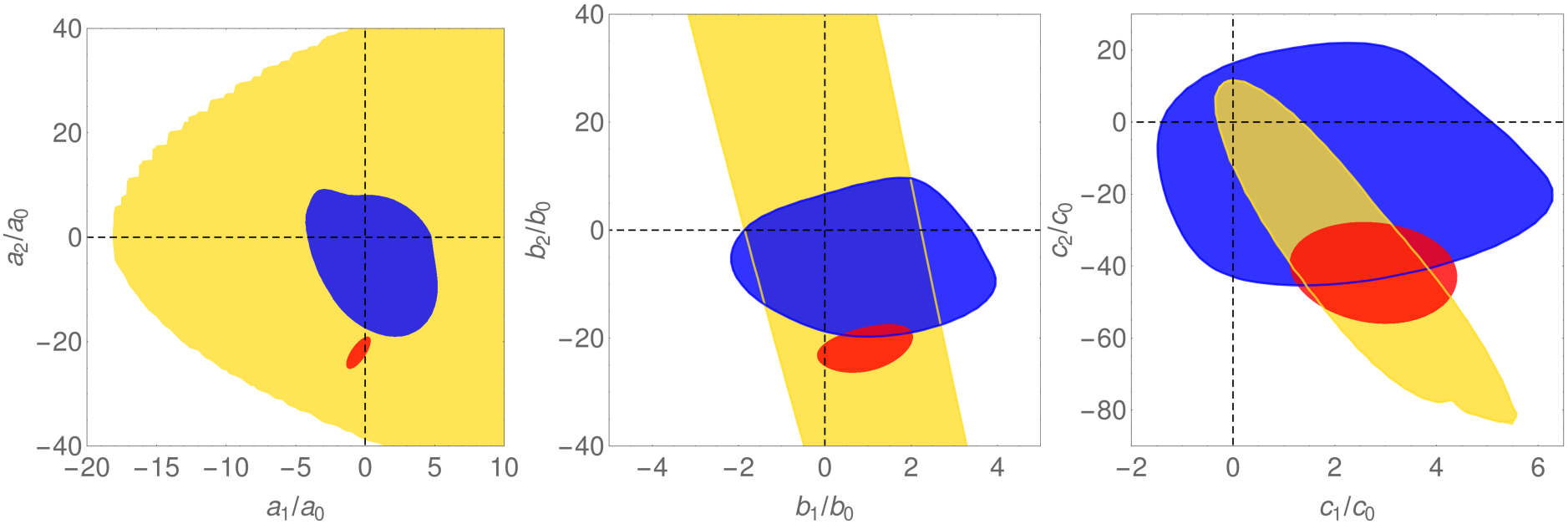


- $B \to D^*$ BGL coefficient ratios from:
  1. Data (Belle'17+'18) + weak unitarity (yellow)
  2. HQE theory fit 2/1/0 (red)
  3. HQE theory fit 3/2/1 (blue)

➥ 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

Lepton-flavour structure: $\mathcal{O}_{V_L}$ [MJ/Straub'18]

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

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

➥ 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 $\lesssim \% \times V_{cb}$

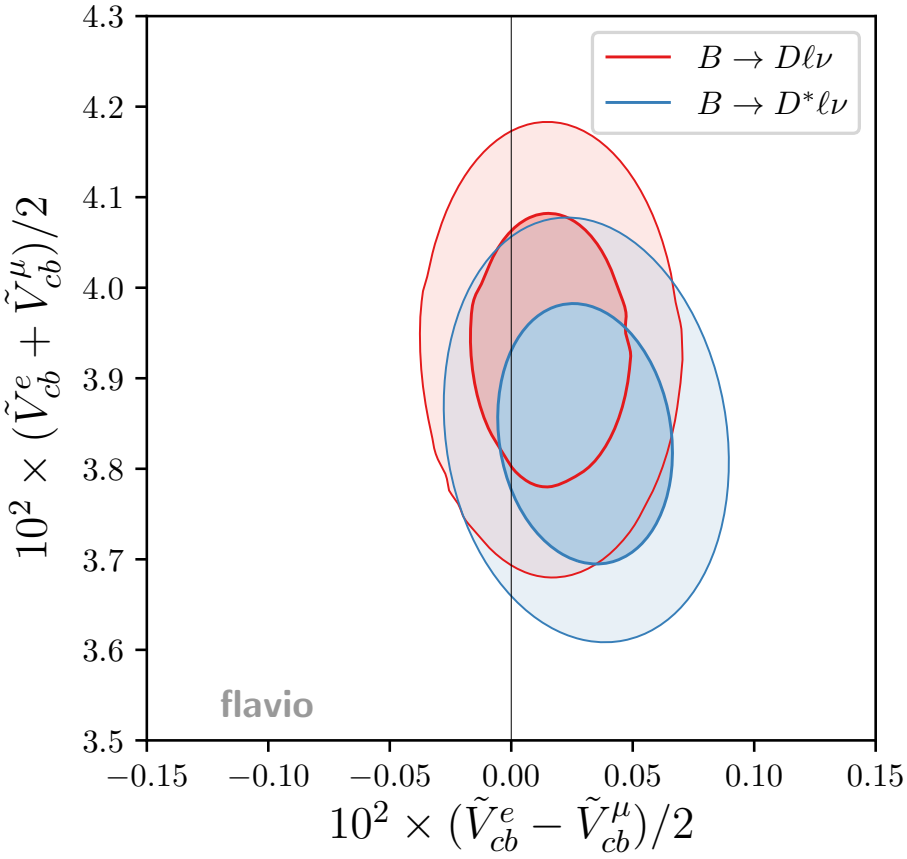
In the following:

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

Plots created with **flavio**

+ independently double-checked

➥ Open source, adaptable

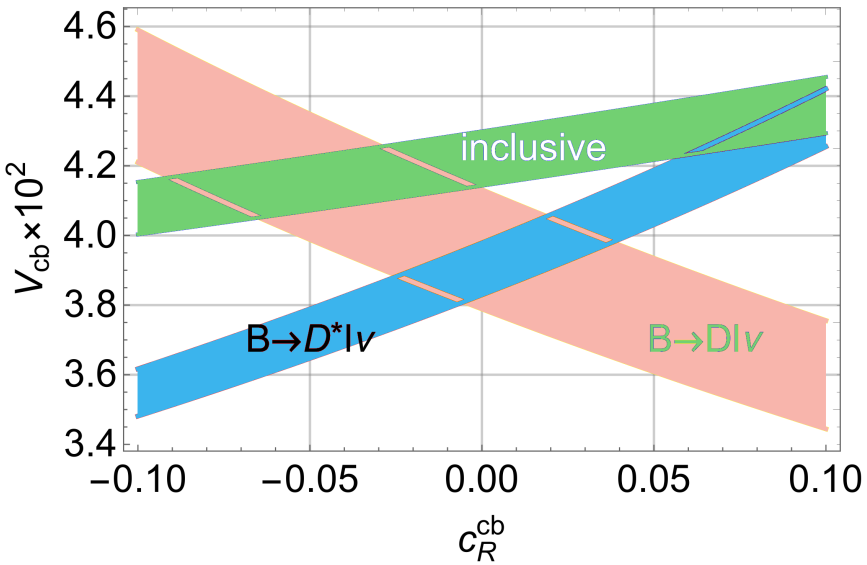


Right-handed vector currents [MJ/Straub'18]

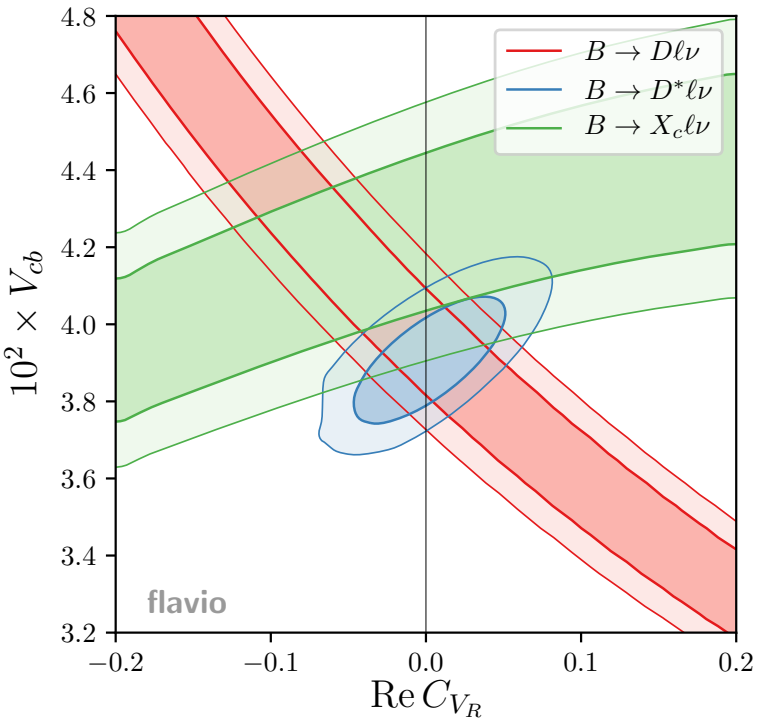
Usual suspect for tension inclusive vs. exclusive [e.g. Voloshin'97]

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]

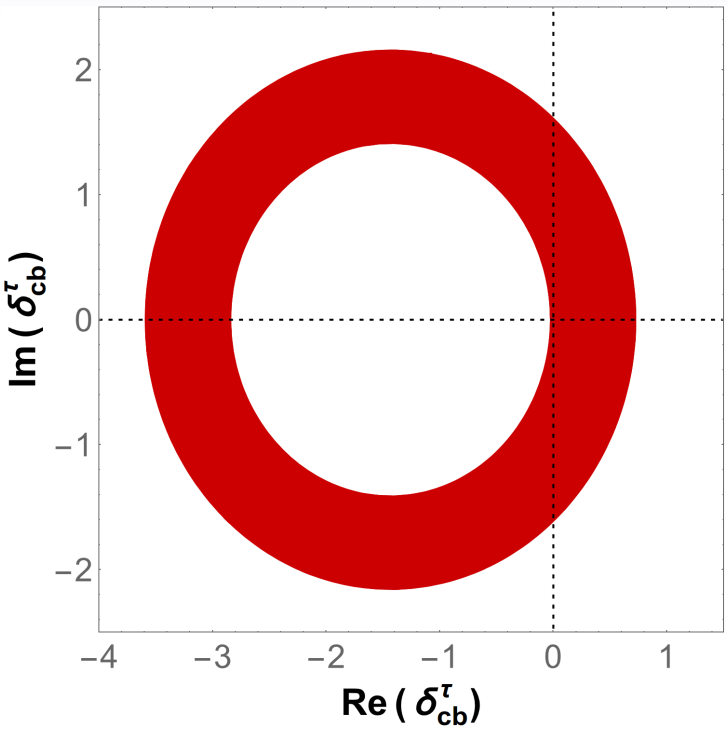


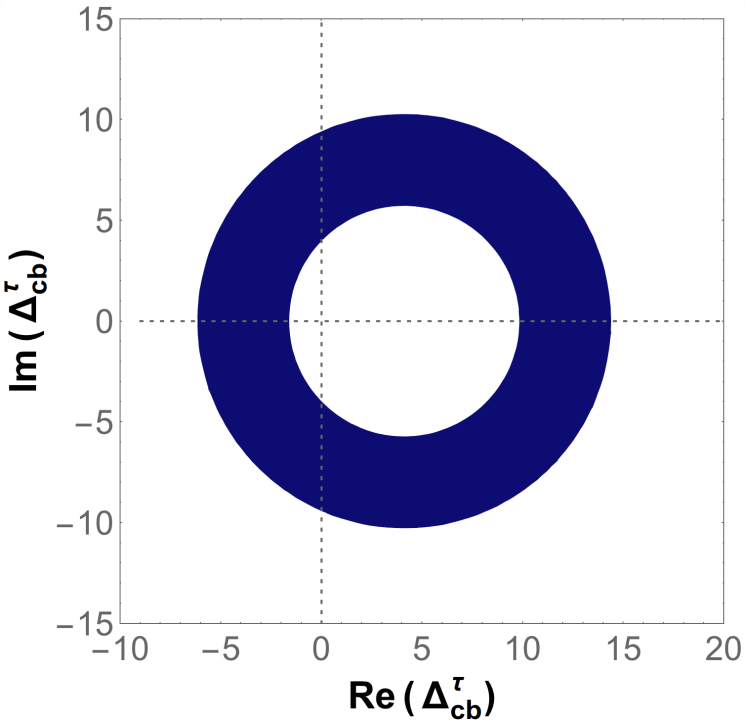
Impact of differential distributions:

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]

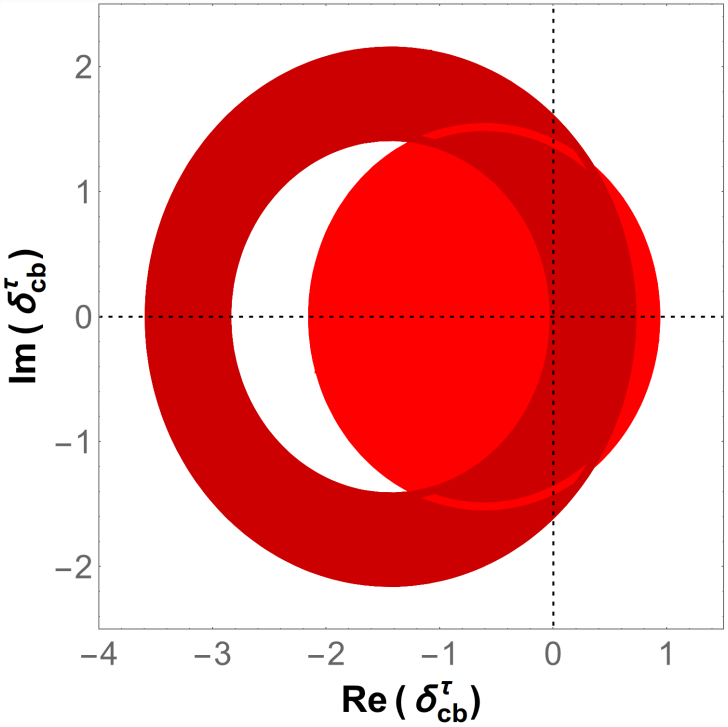


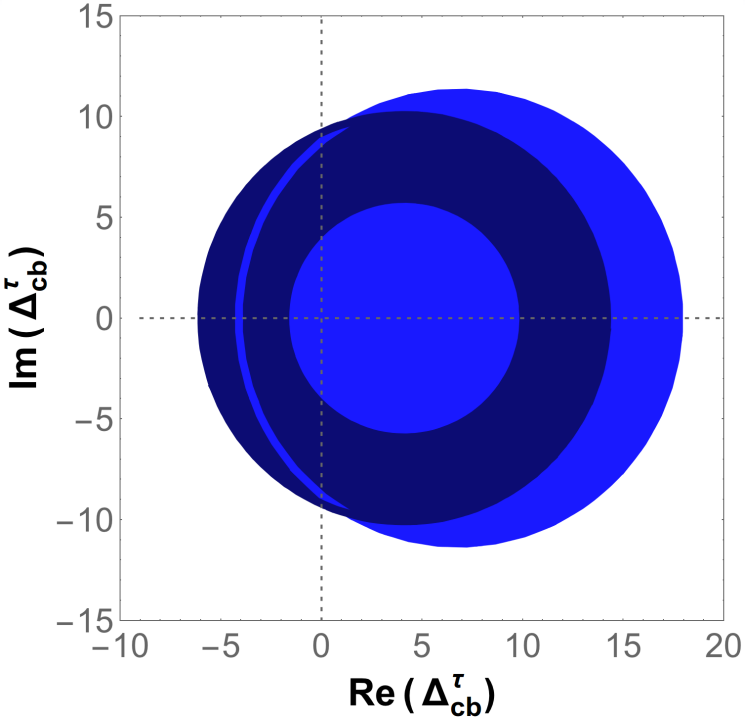


$R(D), R(D^*)$: trivially explainable, but strange

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

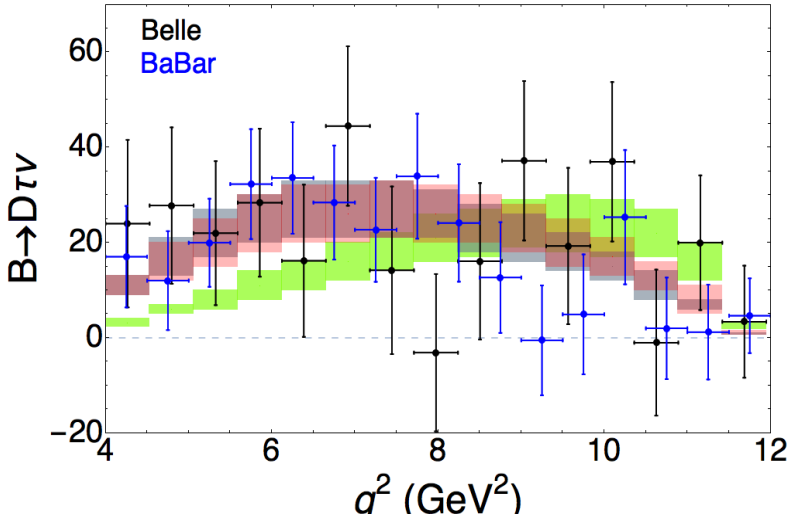
$b \to c\tau\nu$ data and scalar NP [Celis/MJ/Li/Pich'17]



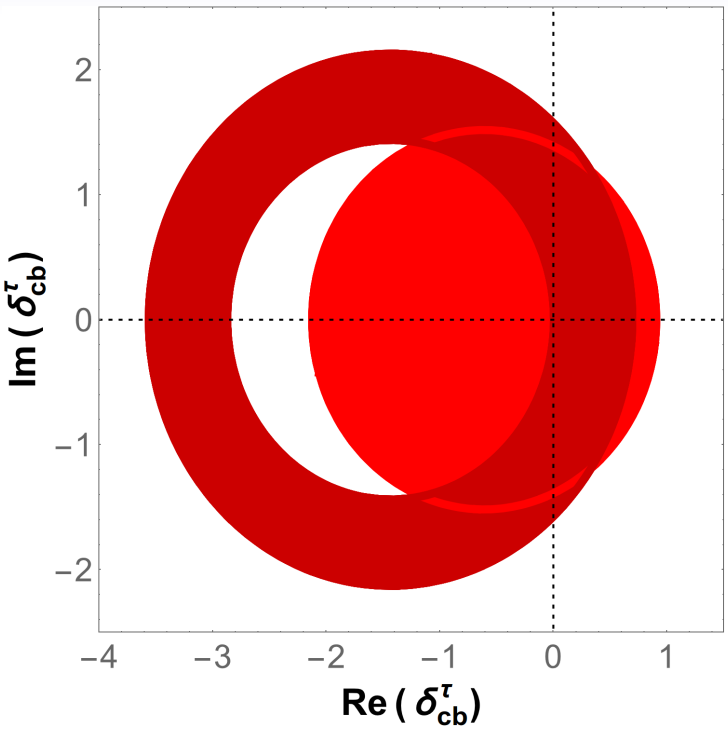


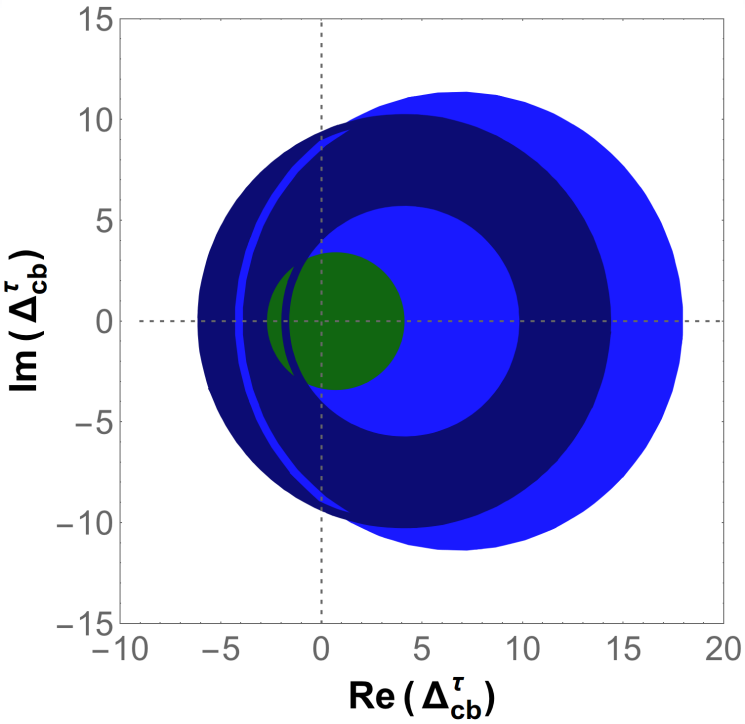
Differential rates:

- 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]

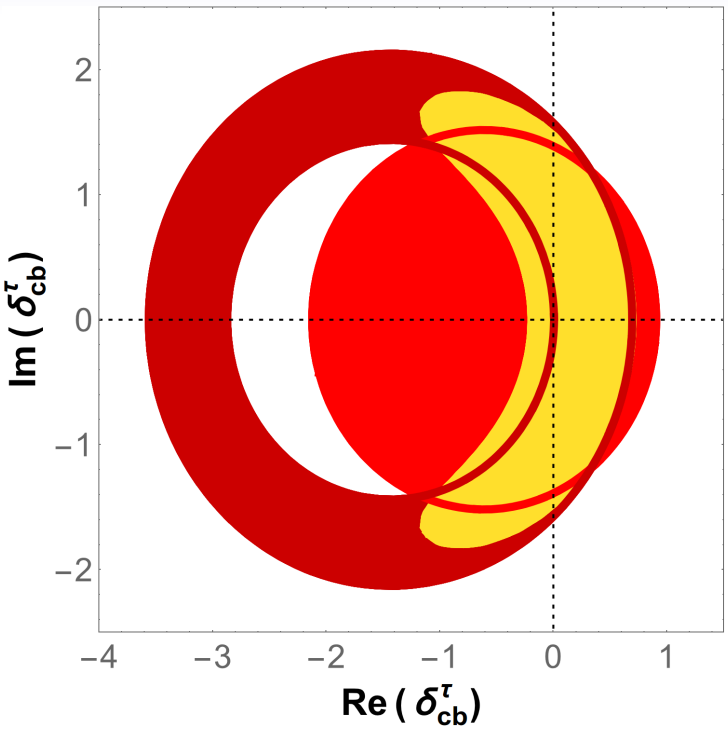


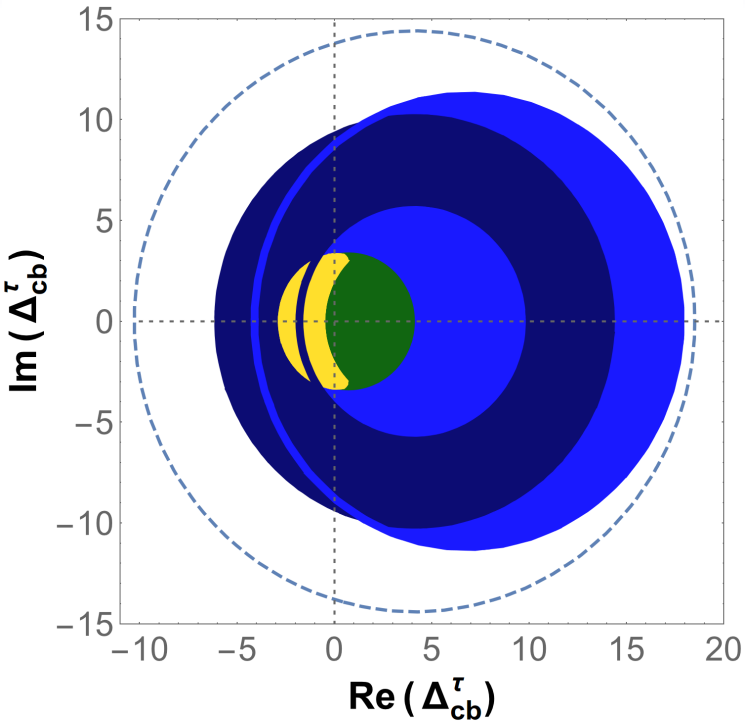


Total width of B_c:

- $B_c \to \tau\nu$ 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]

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

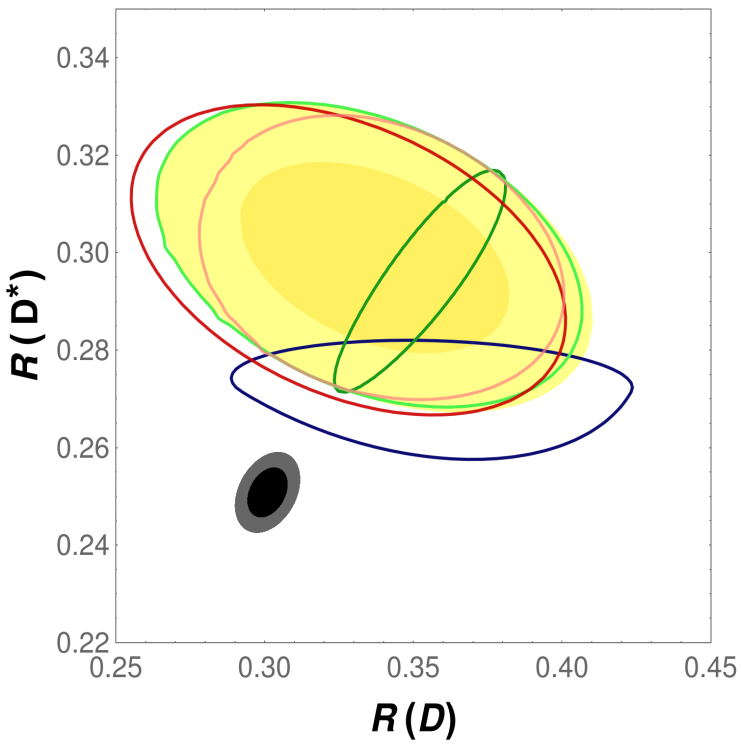
Explanation in 2HDMs possible w/ tension, flavour structure?

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

Fit results for one-mediator scenarios for $B \to D^{(*)}\tau\nu$:



- 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}

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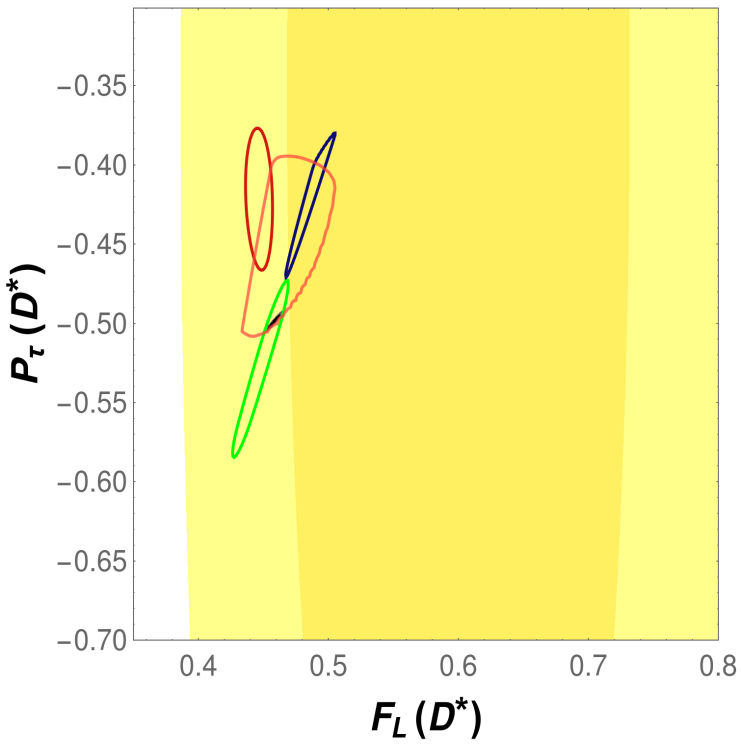
Fit predictions for polarization-dependent $B \to D^*\tau\nu$ observables:



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- SM prediction
- data
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- C_{V_L} and C_{S_R}
- C_{S_L} and C_{S_R}
- $C_T = +4C_{S_L}$@1 TeV
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Differentiating models with $b \to c\tau\nu$ observables

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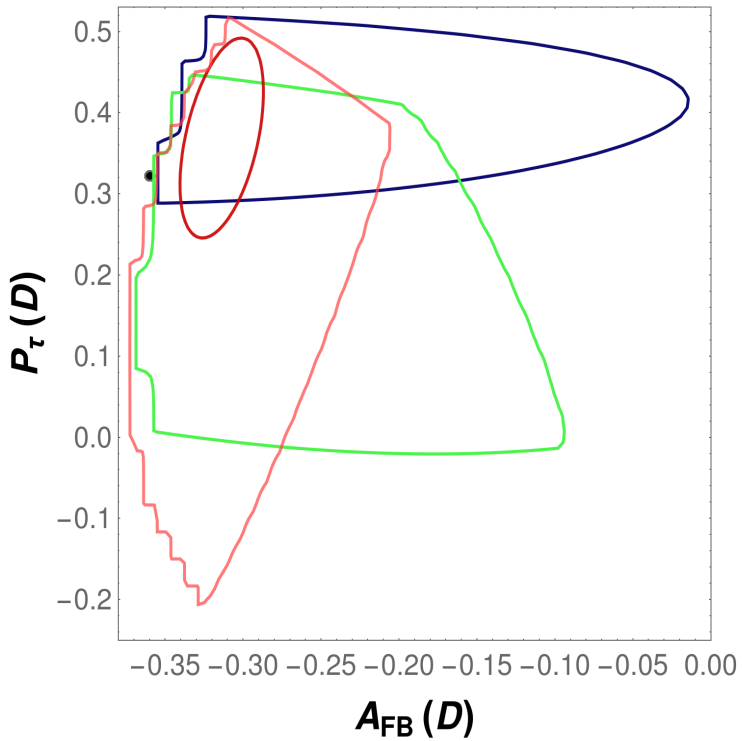
  - ➥ can be related to anomaly in $B \to K^{(*)}\ell^+\ell^-$ modes
- $C_T - C_{S_L}$ from scalar leptoquark
  - ➥ Requires imaginary part in couplings

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



- All coefficients complex
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- 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}

Global fit to $b \to c\tau\nu$ I [Murgui/Peñuelas/MJ/Pich'19]

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

- C_{V_R} 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 $R(D^{(*)})$, $d\Gamma/dq^2(B \to D^{(*)}\tau\nu)$ 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 accomodated
  - Experimental confirmation would have large impact!

Global fit to $b \to c\tau\nu$ II [Murgui/Peñuelas/MJ/Pich'19]

Global minimum: requires either C_{V_L} or C_T

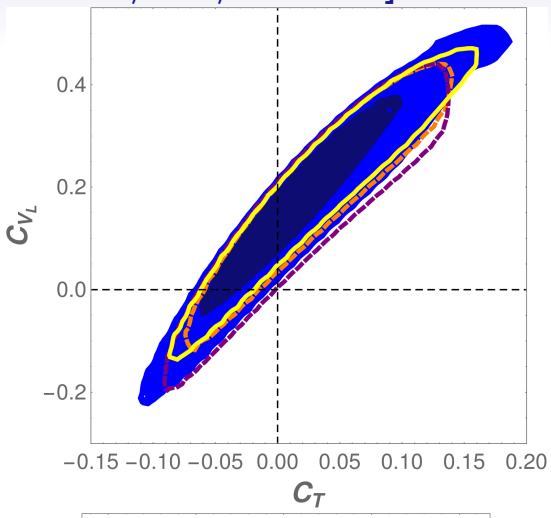
➥ Leptoquarks provide good realizations

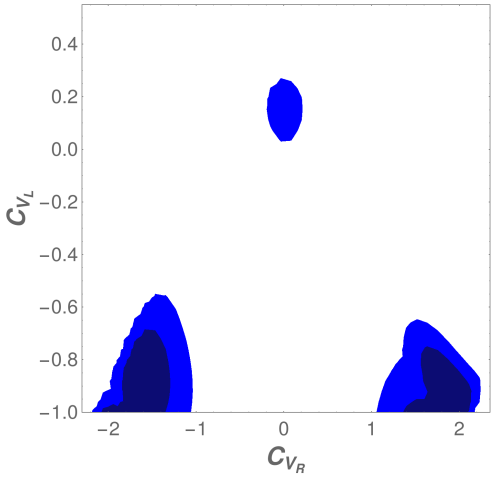
Local minimum: several non-zero WCs

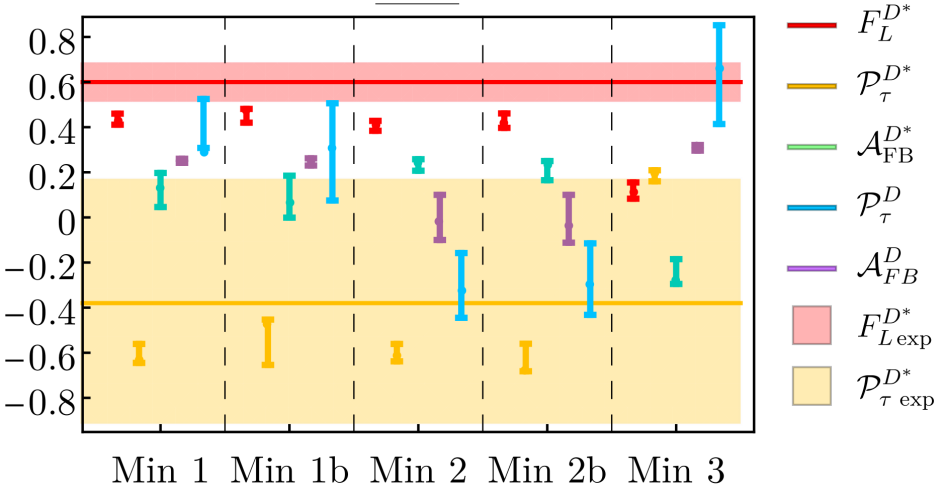
➥ cannot be realized with a single mediator

Allowing for non-universal C_{V_R}:

- Reduces χ^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 $b \to u\tau\nu$ transitions

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

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

➥ Data consistent with SM as well as sizable NP

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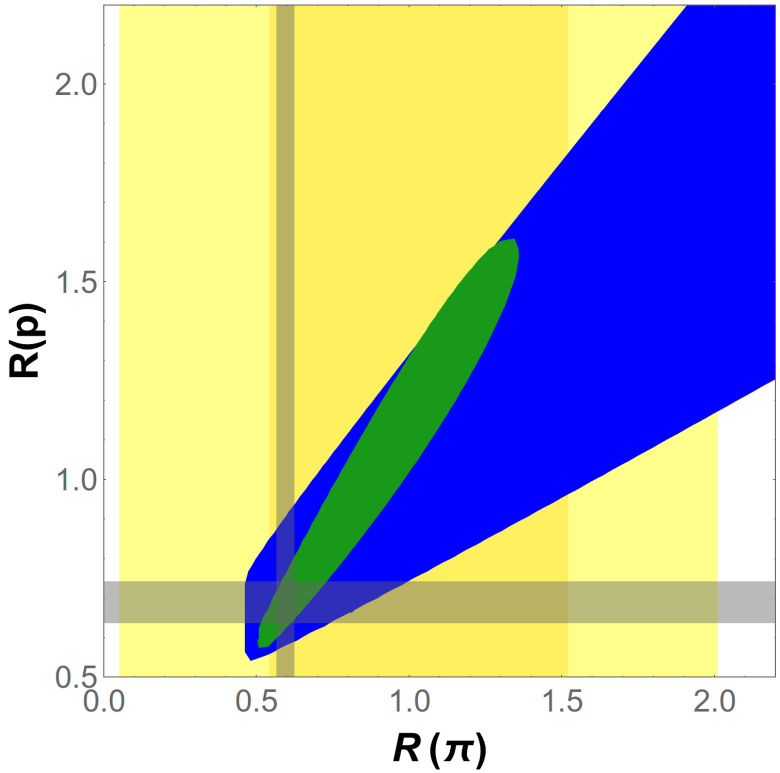
- $R(\tau) \equiv BR(B \to \tau\nu)/BR(B \to \pi\ell\nu)$ about 1.8σ from SM
- $R(\pi)$ not significantly measured yet

➥ Data consistent with SM as well as sizable NP

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

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



More observables needed!

➥ Requires huge data sets

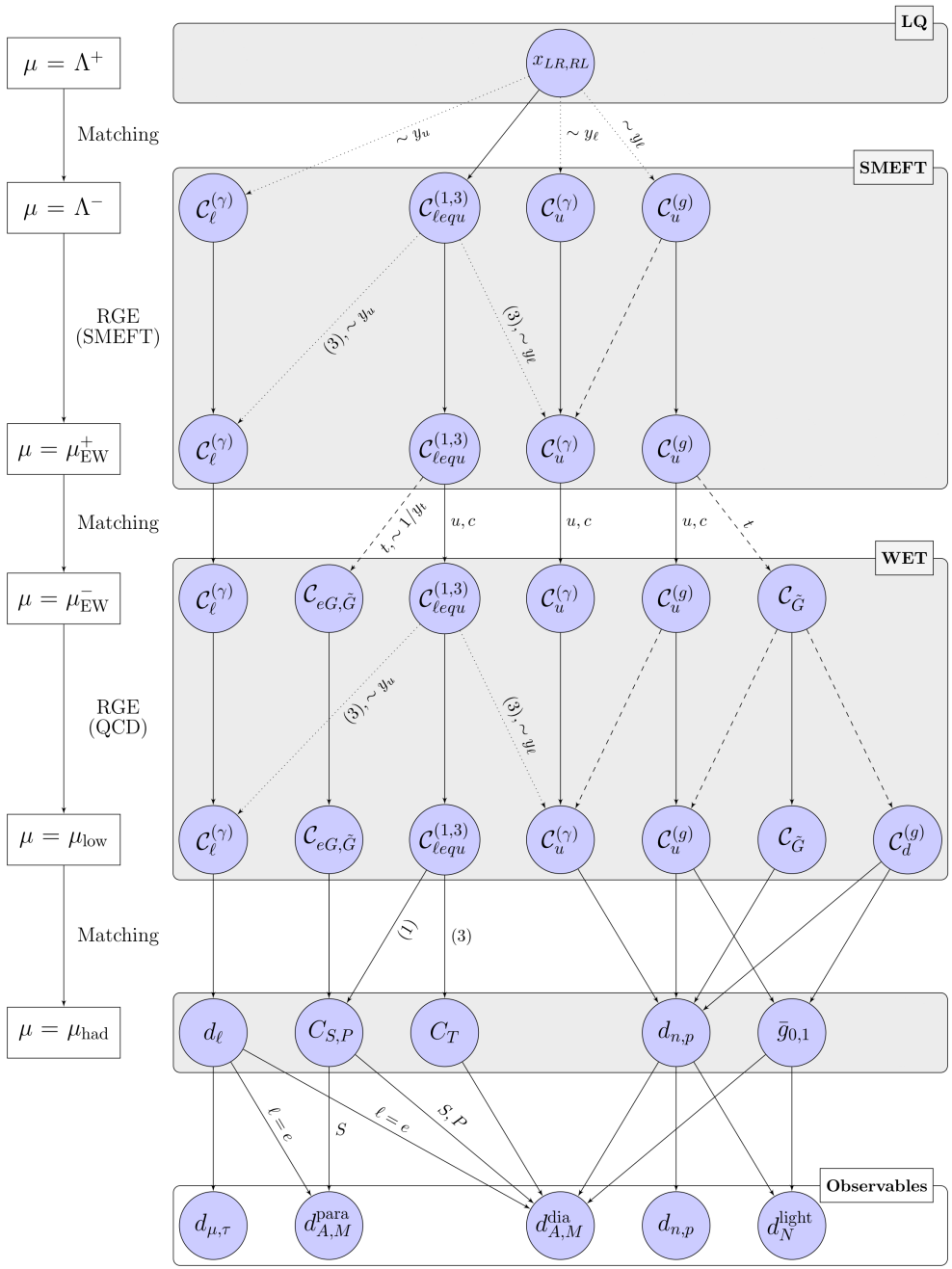
Λ_b: new parameter combinations

$B_s \to K^{(*)}\tau\nu$ decays competitive?

Complementarity LHCb + Belle II

➥ Possible @ CMS?

Indirect constraints: EDMs in sLQ models [Dekens/de Vries/MJ/Vos]



Cascade of EFTs:

Example: R_2 LQ

Tree-level: semileptonic operators

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

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

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

- enter EDM calculations
  ($\rightarrow$ atomic + nuclear MEs)
- MEs have large uncertainties

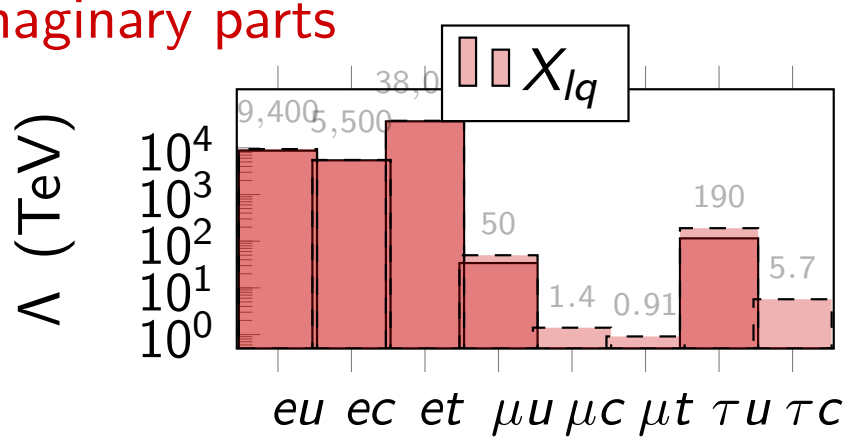
Phenomenological consequences

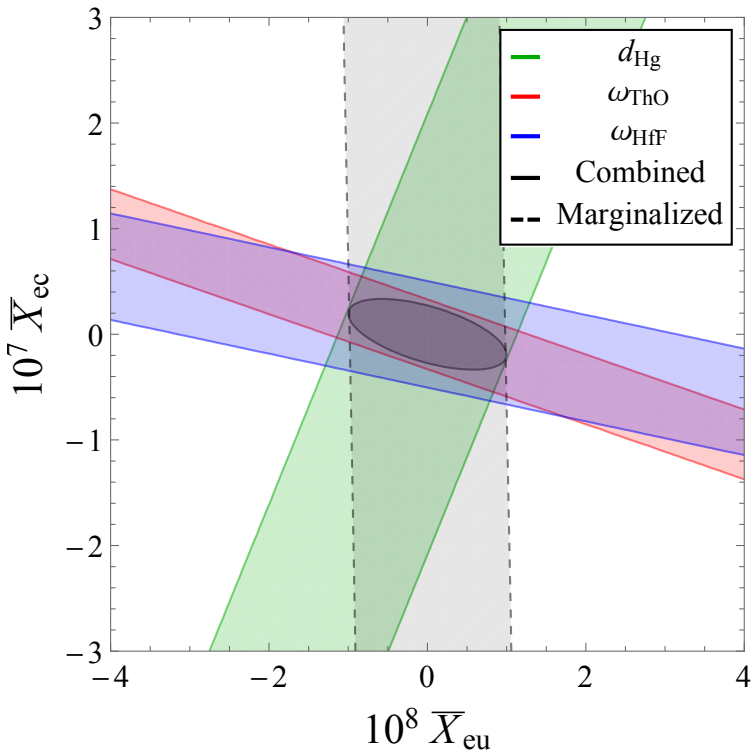
Most observables constrain (mainly) real parts

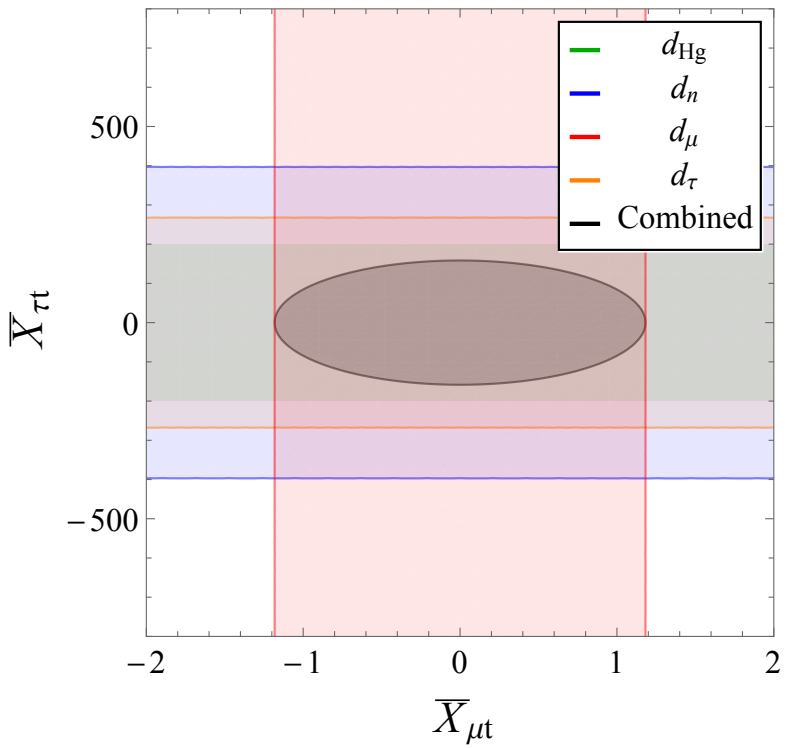
- EDMs constrain complementarily imaginary parts

Flavour-dependence of constraints

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



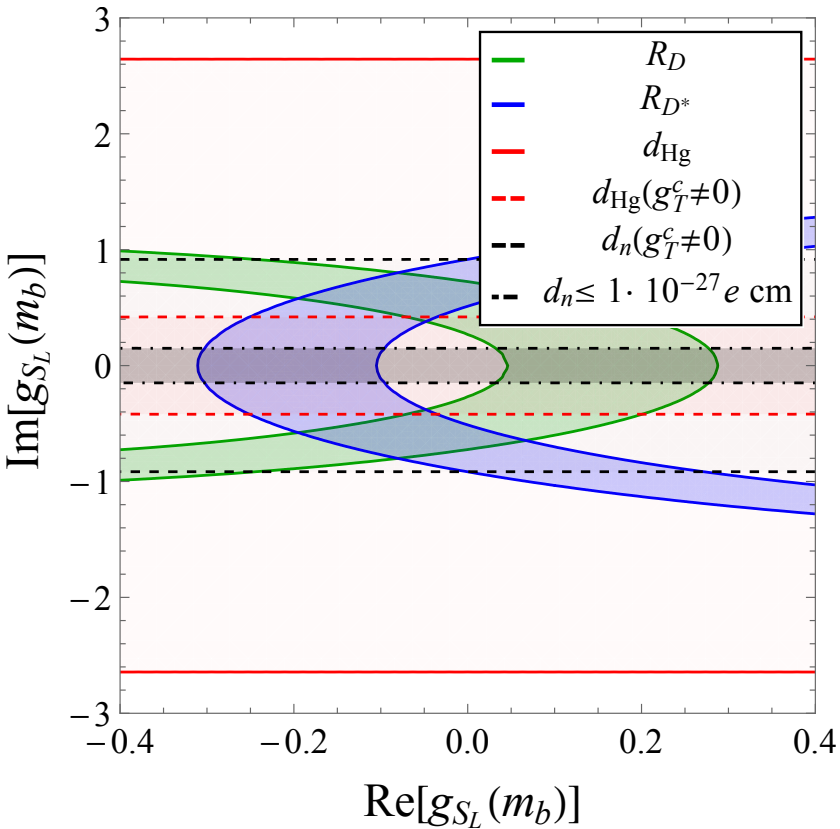




Relation to $R(D) - R(D^*)$ flavour anomaly

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

- Generates $C_{S_L} \sim 4C_T$ (@$\mu_{\rm LQ}$)
- 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

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. 1-2σ 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}^{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

$B \to D\pi$ 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 $\sigma_{\mathrm{BR}}/\mathrm{BR} \sim \mathcal{O}(\%)$

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:

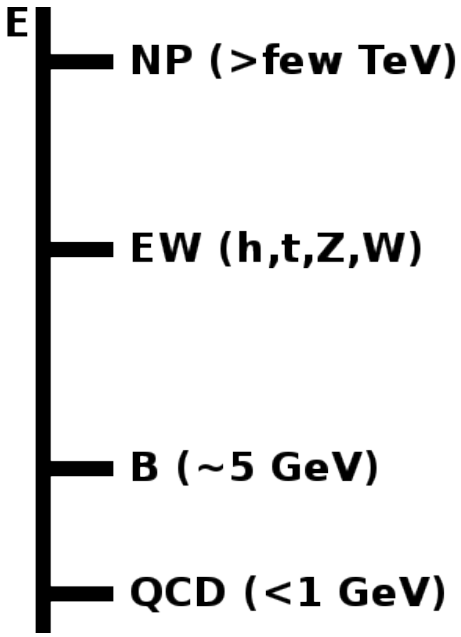
- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in r_{+0}^{HFAG} assume isospin in exclusive decays
  - ➥ This is one thing we want to test!

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

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]

$\boldsymbol{q \to q'\ell\ell}$ **:**

- 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!

$\boldsymbol{q \to q'\ell\nu}$ **:**

- 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]

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	×						

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

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

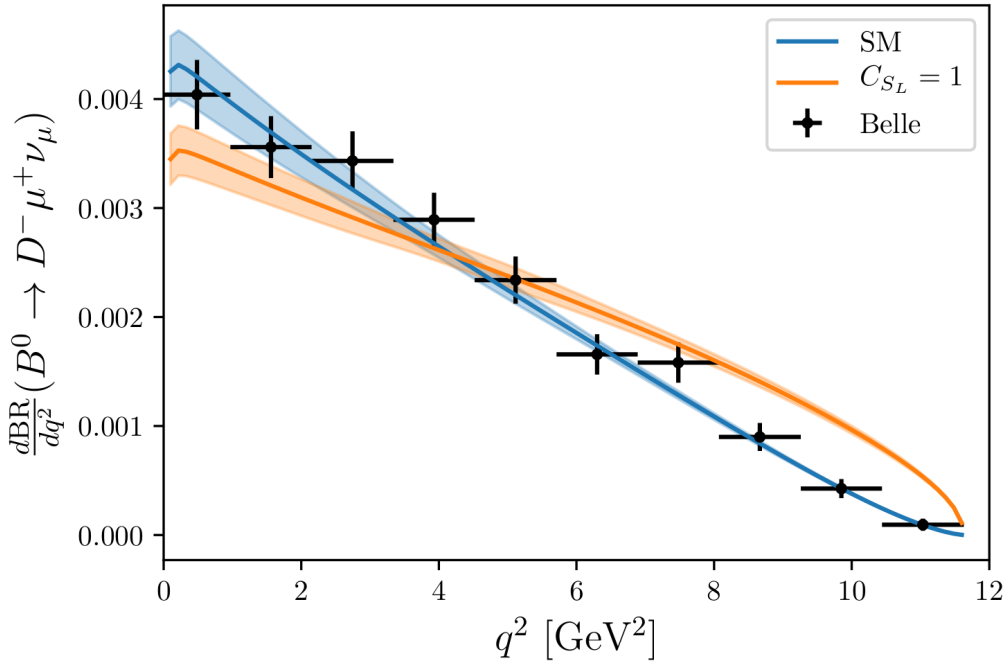
- For fixed V_{cb}, scalar NP increases rates

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

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

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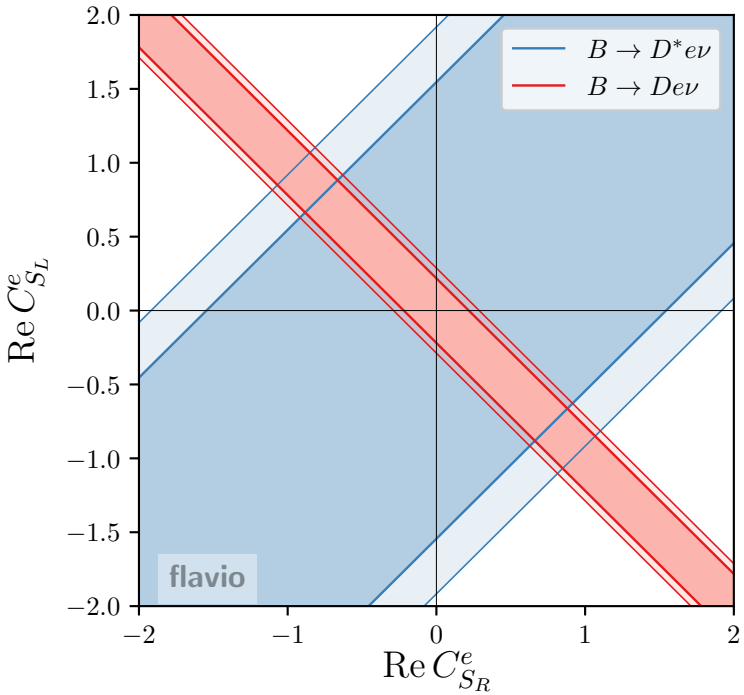
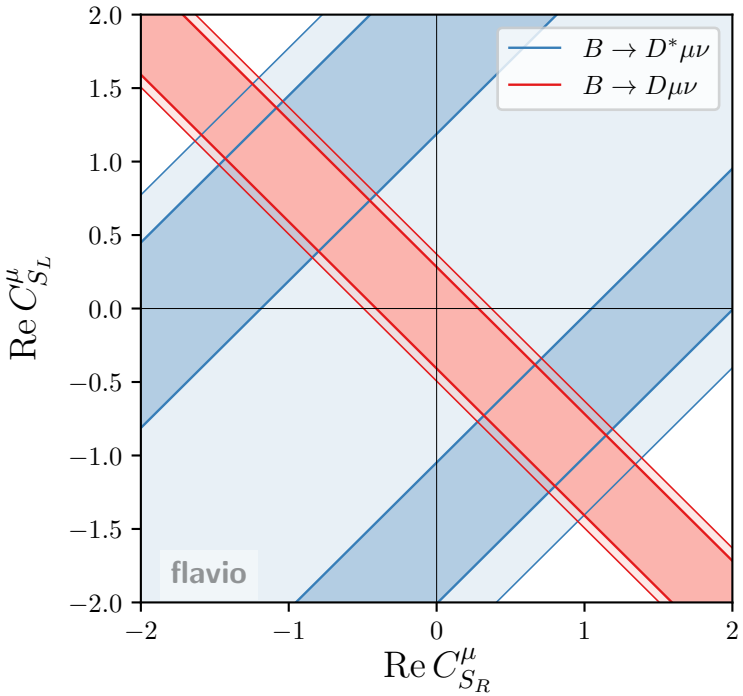
Fit with scalar couplings (generic $C_{S_{L,R}}$):





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

Scalar operators

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

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

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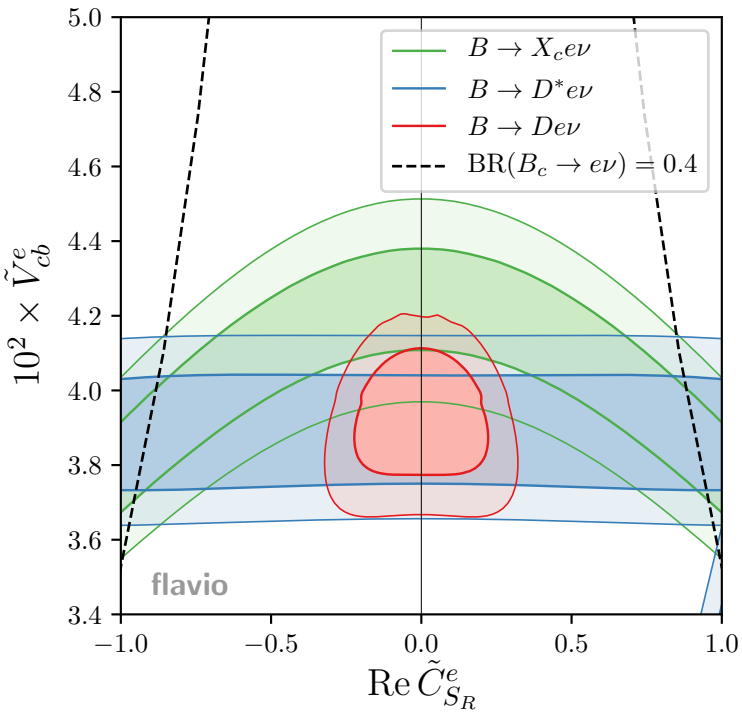
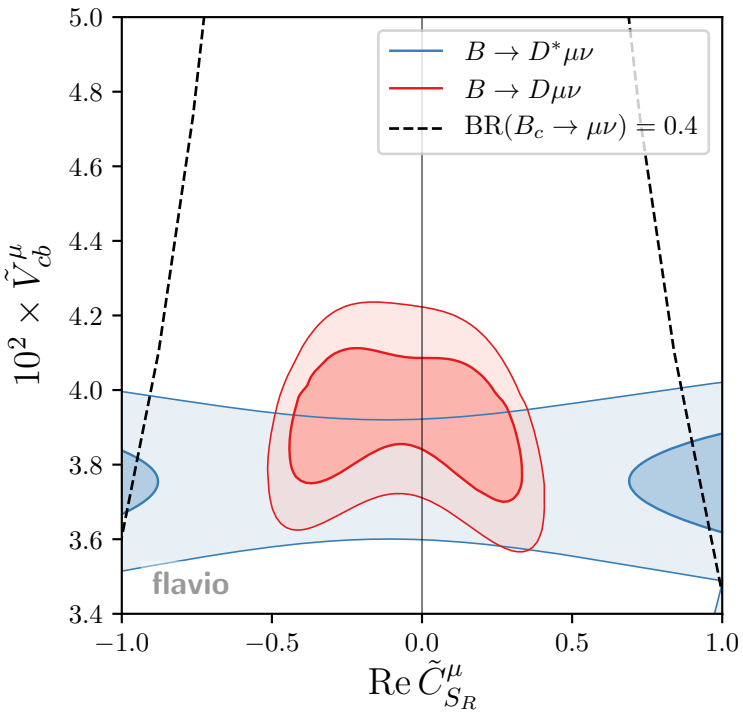
- Endpoint very sensitive to scalar contributions! [see also Nierste+'08]

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

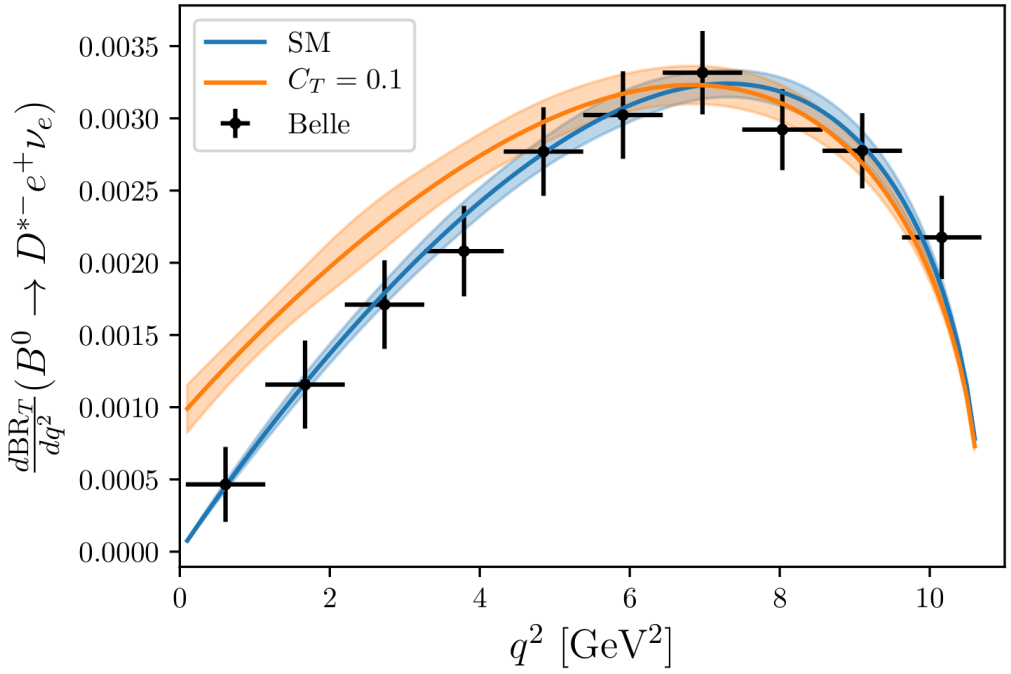
- For fixed V_{cb}, tensor contributions increase rates

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 ($\Gamma_1 = \Gamma_2$):



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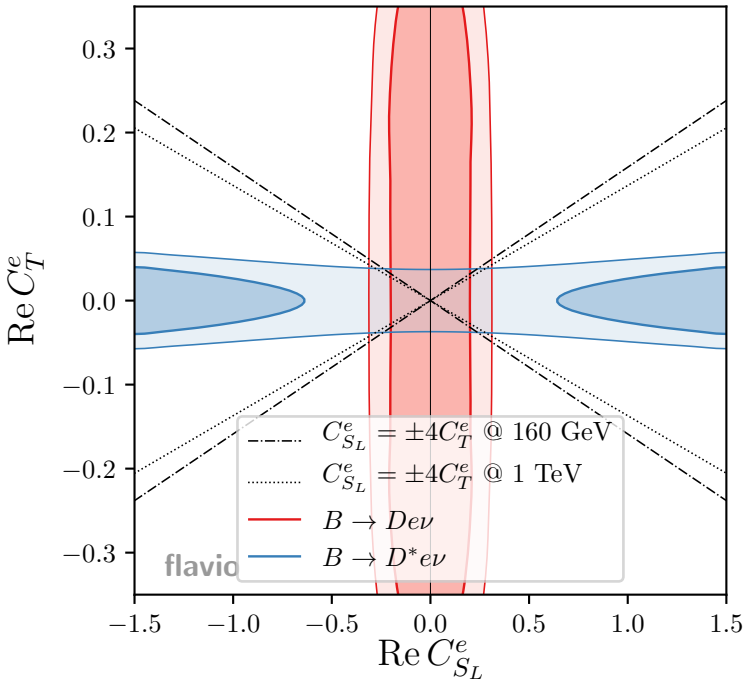
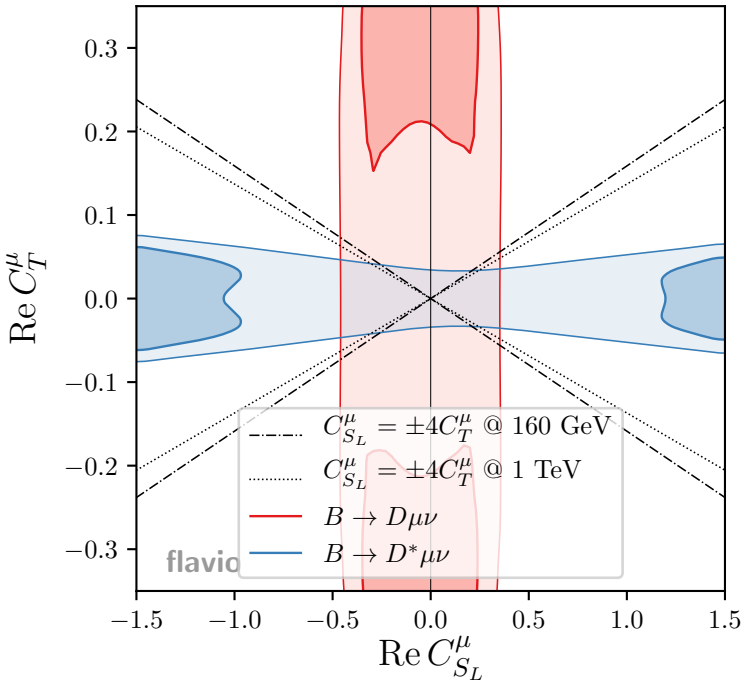
- Endpoint ($q^2 \sim 0$) very sensitive to tensor contributions!

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 $B \to D$