Zurich Phenomenology Workshop 2018

Implications of *B* anomalies: from EFTs to models

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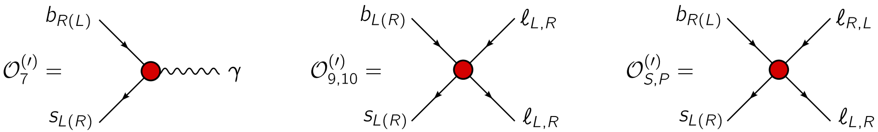
Outline

1. EFT implications
   - $b \to s\ell^+\ell^-$
   - $b \to c\tau\nu$
   - Tree-level models
2. New physics in $b \to c\ell\nu$
3. Flavour Anomalies in MFPC

Effective theory for $b \to s\ell^+\ell^-$

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$



$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu} \qquad O_8^{(\prime)} = \frac{m_b g_s}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_{R(L)}b)G^{a\mu\nu}$$

$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$O_S^{(\prime)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\ell) \qquad O_P^{(\prime)} = (\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)$$

Model-independent fits to $b \to s\ell^+\ell^-$

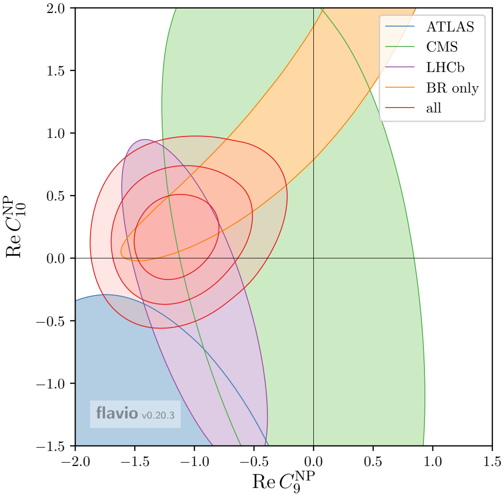
$b \to s\mu^+\mu^-$ only (*not* using R_{K^*}) Altmannshofer et al. 1703.09189

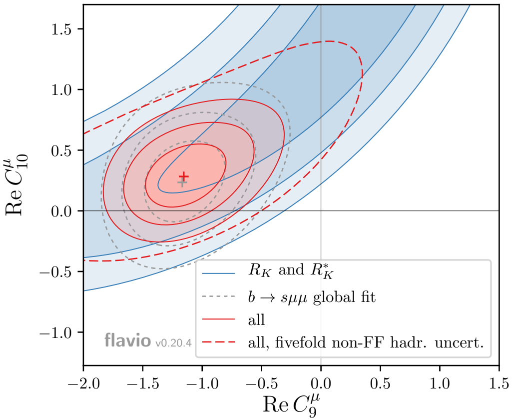
Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.21	$[-1.41, -1.00]$	$[-1.61, -0.77]$	5.2σ
C_{10}^μ	$+0.79$	$[+0.55, +1.05]$	$[+0.32, +1.31]$	3.4σ
$C_9^\mu = -C_{10}^\mu$	-0.67	$[-0.83, -0.52]$	$[-0.99, -0.38]$	4.8σ

R_{K^*} *only* Altmannshofer et al. 1704.05435

Coeff.	best fit	1σ	2σ	pull
C_9^μ	-1.59	$[-2.15, -1.13]$	$[-2.90, -0.73]$	4.2σ
C_{10}^μ	$+1.23$	$[+0.90, +1.60]$	$[+0.60, +2.04]$	4.3σ
$C_9^\mu = -C_{10}^\mu$	-0.64	$[-0.81, -0.48]$	$[-1.00, -0.32]$	4.2σ

C_9^μ vs. C_{10}^μ





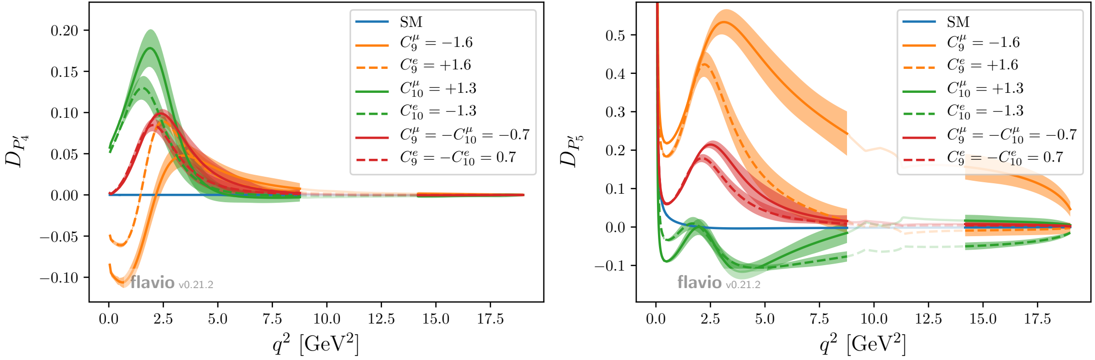
Some comments

- Mind-boggling consistency between $b \to s\mu^+\mu^-$ branching ratios, angular observables, R_K, and R_{K^*}
- Solutions to $R_{K^{(*)}}$ invoking NP in electrons only and large charm effects in $B \to K^*\mu^+\mu^-$: too much of a stretch IMO
- But of course more elaborate models may feature NP in electrons and muons, primed and unprimed, ...

See also Capdevila et al. 1704.05340, Geng et al. 1704.05446, D'Amico et al. 1704.05438, Hurth et al. 1705.06274

Future measurements

… and, yes, angular observables in $B \to K^* e^+ e^-$ will be able to disentangle different hypotheses that all explain $R_{K^{(*)}}$ Talk by J. Matias, L. Silvestrini



Altmannshofer et al. 1704.05435, $D_{P'_5} \equiv Q_5$ first defined in Altmannshofer and Yavin 1508.07009

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Effective theory for $b \to c\tau\nu$

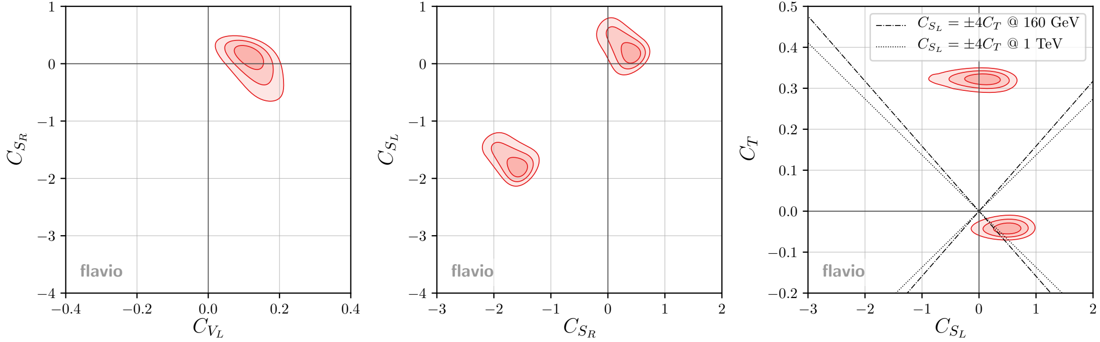
$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left(O_{V_L} + \sum_i C_i O_i + \text{h.c.} \right)$$

$$O_{V_L} = (\bar{c}_L \gamma^\mu b_L)(\bar{\ell}_L \gamma_\mu \nu_{\tau L}) \qquad O_{S_R} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{\tau L}) \qquad O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{\tau L})$$

$$O_{V_R} = (\bar{c}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \nu_{\tau L}) \qquad O_{S_L} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{\tau L})$$

- O_{V_R} is LFU at dimension 6 in SMEFT (can only arise from modification of $\bar{c}_R b_R W$ vertex) $\Rightarrow$ ignore
- Ignoring $b \to c\tau\nu_{e,\mu}$ for simplicity (contributions relevant in concrete models!)

Model-independent fit to $b \to c\tau\nu$



- Fit to R_D, R_{D^*}, $B_c \to \tau\nu$ cf. Akeroyd and Chen 1708.04072
- Not a full fit: $d\Gamma/dq^2$, τ pol., $R_{J/\psi}$ missing

Combined explanations: SMEFT considerations

- Heavy NP must respect $SU(2)_L \times U(1)_Y$ gauge invariance $\Rightarrow D = 6$ SMEFT (ignoring non-linear HEFT) Alonso et al. 1407.7044, Aebischer et al. 1512.02830, …
- Only considering operators that affect $b \to s\mu^+\mu^-$, $b \to c\tau\nu$, violate LFU

$b \to s\mu^+\mu^-$

- $[C_{lq}^{(1)}]^{2223} \to C_9 = -C_{10}$
- $[C_{lq}^{(3)}]^{2223} \to C_9 = -C_{10}$
- $[C_{ld}]^{2223} \to C_9 = C_{10}$

through RG mixing:

- $[C_{lu}]^{2233} \to C_9 = -C_{10}$ Celis et al. 1704.05672

*(basis where $M_{d,l}$ are diagonal)

$b \to c\tau\nu$

- $[C_{lq}^{(3)}]^{33i3} \to C_{V_L}$
- $[C_{ledq}]^{333i*} \to C_{S_R}$
- $[C_{lequ}^{(1)}]^{333i} \to C_{S_L}$
- $[C_{lequ}^{(3)}]^{333i} \to C_T$

through RG mixing: no qualitative change
González-Alonso et al. 1706.00410

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   - Tree-level models
2. New physics in $b \to c\ell\nu$
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Tree-level models

Model	$C_{lq}^{(1)}$	$C_{lq}^{(3)}$	C_{qe}	C_{lu}	C_{ledq}	$C_{lequ}^{(1)}$	$C_{lequ}^{(3)}$
Z'	×		×	×			
V'		×					
H'					×	×	
S_1	×	×				×	×
R_2			×	×		×	×
S_3	×	×					
U_1	×	×			×		
U_3	×	×					
V_2			×		×		
$\tilde{V}_2$				×			

1. EFT implications
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New physics in $b \to c\ell\nu$ Jung and Straub 1801.01112

- We have hints for e-μ LFUV in $b \to s$ and μ-τ LFUV in $b \to c$
- Elephant in the room: should look for μ-τ LFUV in $b \to s$ and e-μ LFUV in $b \to c$ as well!

$b \to c\ell\nu$ with $\ell = e, \mu$

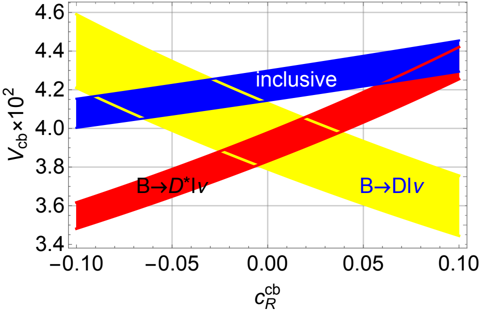
- Exclusive $B \to D^{(*)}\ell\nu$ & inclusive $B \to X_c\ell\nu$ use to measure V_{cb}
- Long-standing tension, hard to solve with NP Crivellin and Pokorski 1407.1320, Colangelo and De Fazio 1611.07387

$b \to c\ell\nu$: recent developments

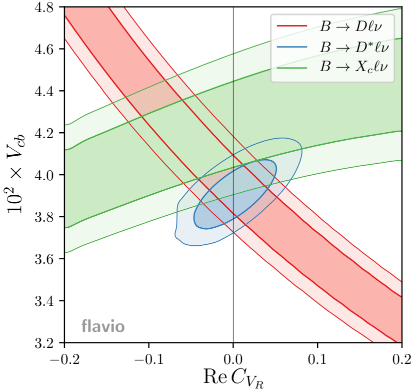
- Updated lattice FFs Talk by A. Kronfeld
  - $B \to D$ Na et al. 1505.03925, Bailey et al. 1503.07237
  - $B \to D^*$ zero recoil Bailey et al. 1403.0635, Harrison et al. 1711.11013
- New measurements (BaBar, Belle)
  - Differential branching ratios (not dependent on FF model)
  - Angular observables in $B \to D^*\ell\nu$
  - Some analysis split by e/μ
- Form factor discussion Talk by P. Gambino
  - CLN uncertainties underestimated in the past Bernlochner et al. 1703.05330, Bigi et al. 1707.09509
  - V_{cb} fits: can use BGL/BCL and fit FF from data Bigi and Gambino 1606.08030, Grinstein and Kobach 1703.08170, Bigi et al. 1703.06124, Bernlochner et al. 1708.07134
  - here: use CLN with proper error estimates, lattice, LCSR Faller et al. 0809.0222 to *pre*-dict FFs and extract NP

Right-handed currents

(Recall C_{V_R} predicted to be LFU at $D = 6$ in SMEFT)



update of Crivellin and Pokorski 1407.1320



- Differential/angular distributions in $B \to D^*\ell\nu$ *alone* allow to exclude large RHC

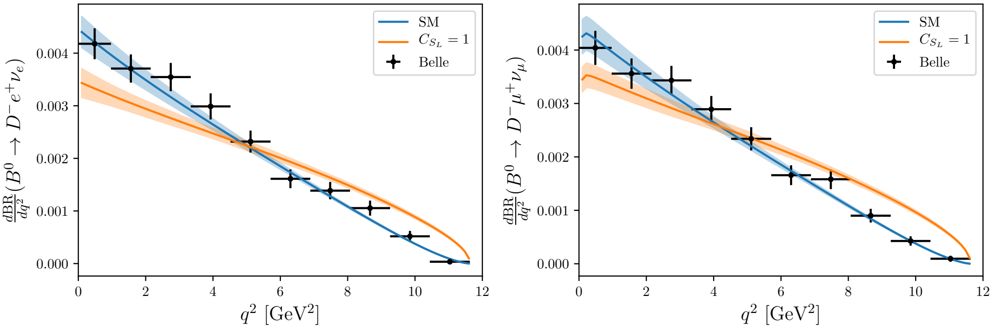
Scalar operator: endpoint effect

- At $q^2 \to q^2_{\text{max}}$, SM & scalar contribution have behave differently:

$$\frac{d\Gamma(B \to D\ell\nu)}{dq^2}\Big|_{\text{SM}} \propto f_+^2 \left(q^2 - q^2_{\text{max}}\right)^{3/2} \qquad \frac{d\Gamma(B \to D\ell\nu)}{dq^2}\Big|_{C_{S_{L,R}}} \propto f_0^2 |C_{S_R} + C_{S_L}|^2 \left(q^2 - q^2_{\text{max}}\right)^{1/2}$$

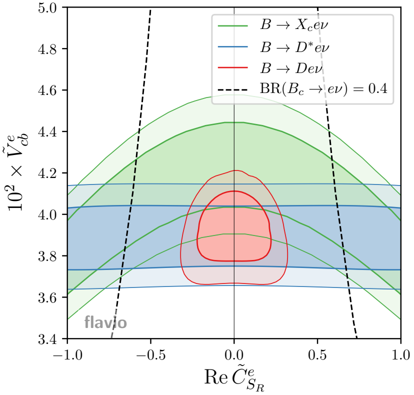
- Last bin is extremely sensitive to scalar operators (much more than total rate!)

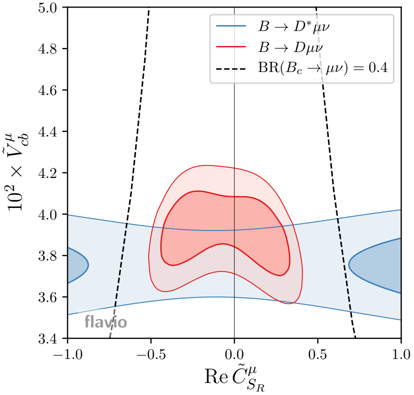
cf. Nierste et al. 0801.4938, Hiller and Zwicky 1312.1923



Scalar operators

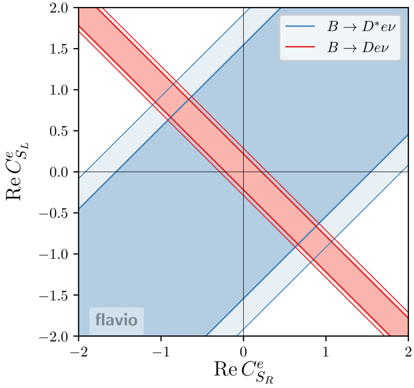
- Fit to C_{S_R} and $\tilde{V}_{cb} = V_{cb}(1 + C_{V_L})$ (as e.g. in U_1 and V_2 LQ models)
- Large effects excluded by $B \to D\ell\nu$ due to endpoint sensitivity!
- $B \to D\ell\nu$ stronger than B_c lifetime constraint (thanks to J. Camalich)

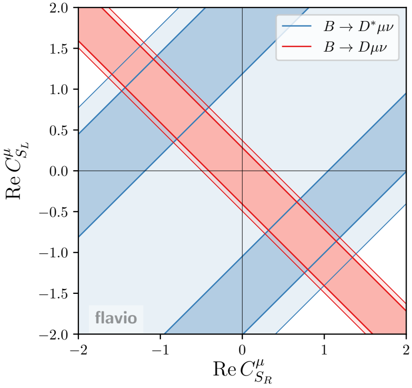




Scalar operators

- C_{S_R} vs. C_{S_L} (e.g. charged Higgs)
- slight preference for non-standard values $C^{\mu}_{S_R} \sim -C^{\mu}_{S_L}$ in muons (but large values in conflict with B_c lifetime)



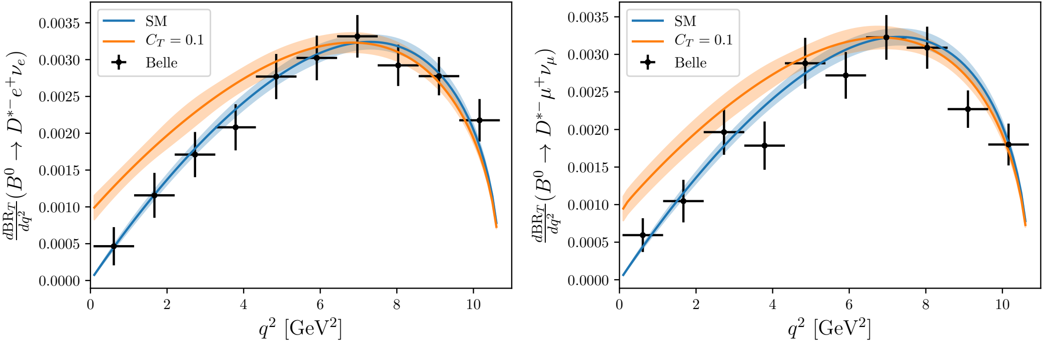


Tensor operator: endpoint effect

- At $q^2 \to 0$, SM contribution to $B \to D^*\ell\nu$ is fully longitudinal, tensor contribution isn't

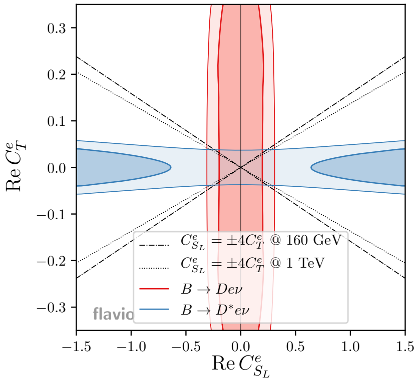
$$\frac{d\Gamma_T(B \to D^*\ell\nu)}{dq^2} \propto q^2\, C_{V_L}^2 \left(A_1(0)^2 + V(0)^2\right) + 16 m_B^2\, C_T^2\, T_1(0)^2 + O\left(\frac{m_{D^*}^2}{m_B^2}\right)$$

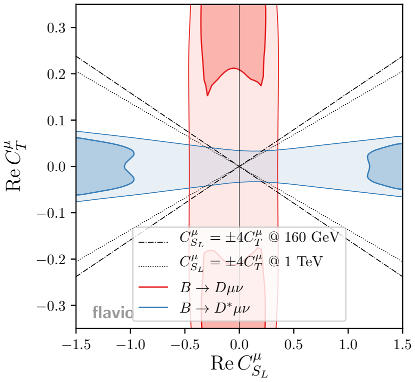
- First bin of Γ_T is extremely sensitive to C_T (much more than total rate!)



Fit: scalar vs. tensor operator

- Fit to C_{S_L} and C_T
- $C_{S_L} = +4C_T$ predicted at matching scale by R_2, $C_{S_L} = -4C_T$ by S_1
- $B \to D\ell\nu$ and $B \to D^*\ell\nu$ nicely complementary due to endpoint effects





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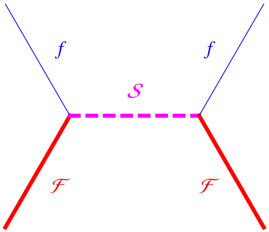
Fundamental Partial Compositeness (FPC) Sannino et al. 1607.01659

- Partial compositeness: crucial ingredient of viable composite Higgs models

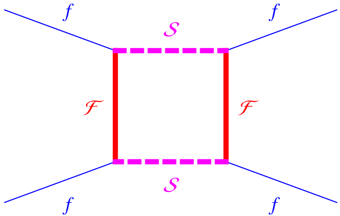
$$\mathcal{L} \supset \lambda q \mathcal{Q}$$

- Composite fermion $\mathcal{Q}$: hard to realize if $\mathcal{Q}$ is "baryon"
- UV completion possible if $\mathcal{Q}$ is scalar-fermion bound state: $\mathcal{Q} \sim \mathcal{F}\mathcal{S}$



Fermion masses

$f\,f\,\mathcal{F}\mathcal{F} \sim f\,f\,H$

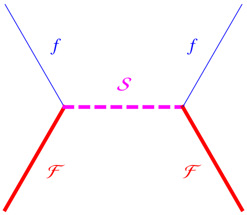


Flavour physics

f^4

Minimal FPC Cacciapaglia et al. 1704.07845

- Gauge group Sp(N_{TC})
- NB: EW symmetry broken by (composite) Higgs VEV, not by condensate!
- Global symmetry breaking coset SU(4)/Sp(4) $\sim$ SO(6)/SO(5)
- Scalar sector invariant under global Sp($2N_{\mathcal{S}}$) $=$ Sp$(24)_{\mathcal{S}}$



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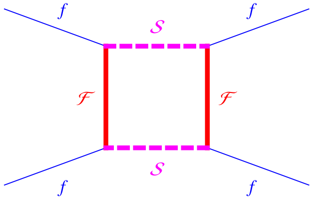

Flavour physics

f^4

EFT for FPC

- EFT with operators invariant and the full global symmetries of the theory $\to$ match to weak effective theory
- All low-energy phenomenology fixed in terms of fundamental parameters of the UV theory and Wilson coefficients of TC operators

$$\mathcal{O}^1_{4f} = \frac{1}{64\pi^2\Lambda_2}(\psi^{i_1}{}_{a_1}\psi^{i_2}{}_{a_2})(\psi^{\dagger\,i_3 a_3}\psi^{\dagger\,i_4 a_4})\Sigma^{a_1a_2}\Sigma^\dagger_{a_3a_4}\epsilon_{i_1i_2}\epsilon_{i_3i_4}$$

$$\ldots$$

$$\mathcal{O}^8_{4f} = \frac{1}{128\pi^2\Lambda_2}(\psi^{i_1}{}_{a_1}\psi^{i_2}{}_{a_2})(\psi^{i_3}{}_{a_3}\psi^{i_4}{}_{a_4})\Sigma^{a_1a_2}\Sigma^{a_3a_4}\left(\epsilon_{i_1i_4}\epsilon_{i_2i_3} - \epsilon_{i_1i_3}\epsilon_{i_2i_4}\right)$$

$$\mathcal{O}_{\Pi f} = \frac{i}{32\pi^2}(\psi^{\dagger\,i_1a_1}\bar{\sigma}_\mu\psi^{i_2}{}_{a_2})\,\Sigma^\dagger_{a_1a_3}\overleftrightarrow{D}^\mu\Sigma^{a_3a_2}\,\epsilon_{i_1i_2}$$

EFT for FPC

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$$\ldots$$

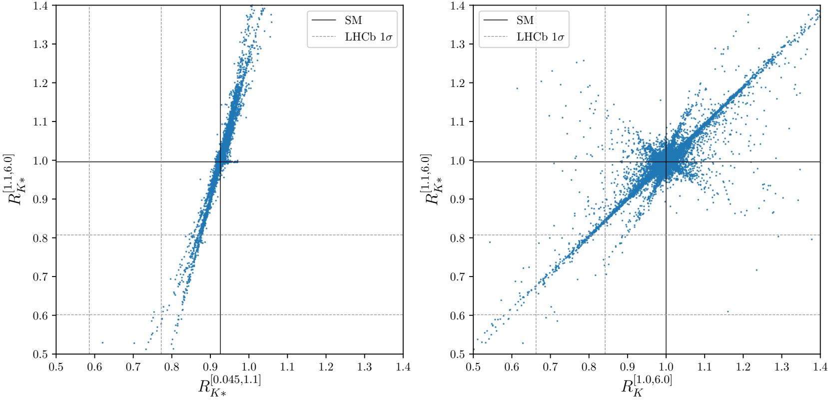
$$\mathcal{O}^8_{4f} = \frac{1}{128\pi^2\Lambda_2}(\psi^{i_1}{}_{a_1}\psi^{i_2}{}_{a_2})(\psi^{i_3}{}_{a_3}\psi^{i_4}{}_{a_4})\Sigma^{a_1 a_2}\Sigma^{a_3 a_4}\left(\varepsilon_{i_1 i_4}\varepsilon_{i_2 i_3} - \varepsilon_{i_1 i_3}\varepsilon_{i_2 i_4}\right)$$

$$\mathcal{O}_{\Pi f} = \frac{i}{32\pi^2}(\psi^{\dagger\, i_1 a_1}\bar{\sigma}_\mu \psi^{i_2}{}_{a_2})\, \Sigma^\dagger_{a_1 a_3} \overleftrightarrow{D}^\mu \Sigma^{a_3 a_2}\ \varepsilon_{i_1 i_2}$$

- Now: numerical analysis, reproducing masses & mixings of (partially composite) SM spectrum, varying all free parameters (fundamental & “TC-hadronic”)

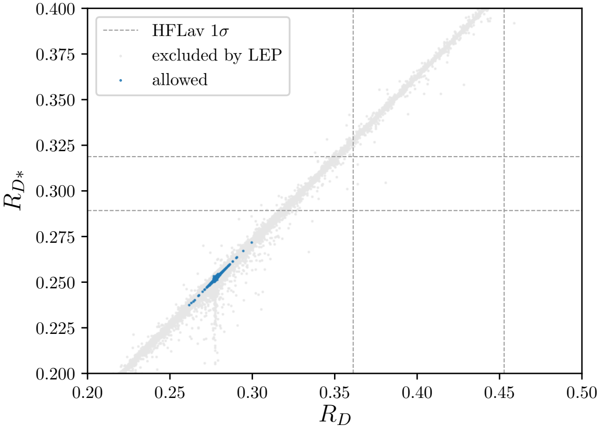
Sannino et al. 1712.07646

Predictions for $R_{K^{(*)}}$ Sannino et al. 1712.07646



- Taking into account constraints from Z pole EWPT, $\Delta F = 2$
- We can explain all $R_{K^{(*)}}$ anomalies!

Predictions for $R_{D^{(*)}}$ Sannino et al. 1712.07646



- Taking into account LEP Z pole constraints, we cannot explain R_D and R_{D^*}

Conclusions

1. EFT implications of anomalies
   - Consistent picture, WC patterns well understood
   - Time for model building [talks]
2. New physics in $b \to c\ell\nu$ ($\ell = e, \mu$)
   - Motivated by $b \to c\tau\nu$ & V_{cb} tensions
   - $B \to D^*\ell\nu$ angular distribution alone constrains RH currents
   - kinematic endpoint effects strongly constrain scalar & tensor effects
3. Flavour anomalies in Minimal Fundamental Partial Compositeness
   - UV completion for composite Higgs models
   - $R_{K^{(*)}}$ anomalies explained while satisfying $\Delta F = 2$ & EWPT
   - Slight enhancement of $R_{D^{(*)}}$ possible, but solution of anomalies precluded by LEP

Backup

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Numerics powered by
`flavio` – a Python package for flavour phenomenology in the SM & beyond

- Documentation: `https://flav-io.github.io/`
- Code: `https://github.com/flav-io/flavio`

Now directly supports new physics in terms of SMEFT operators

Aebischer et al. 1712.05298