New results on $b \to c\tau\bar{\nu}$ and ϵ_K

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June 12–17, 2016

Flavor: new/old players besides LHC(b)

- Belle II is approaching — time to make genuine predictions is shrinking

  recent months: $e^{\pm}$ circulated in SuperKEKB rings (~ 0.5 A, 1576 bunches)

- NA62 this year: ~ 200 days run, at SM level ~ 50 events in $K^+ \to \pi^+ \nu\bar\nu$

- Interesting to think about:
  - What can be done with $10 - 100$ times more data, that has not been done?
  - What important / useful theory predictions have not been made?
  - New ideas? Room for major developments?

    Order of magnitude more data always triggered new ideas & methods

sc final focus, Dec. 25, 2015

Dec. 26, 2015

Outline

- $B \to D^{(*)}\tau\bar{\nu}$ is currently the most significant deviation from the SM
  - MFV models, leptoquarks [M. Freytsis, ZL, J. Ruderman, PRD 92 (2015) 054018, arXiv:1506.08896]
    "deconstructed ambulance chasing"
  - Suppress e & μ instead of enhancing τ? [M. Freytsis, ZL, J. Ruderman, to appear]
  - $B \to D^{**}\ell\bar{\nu}$ decays [F. Bernlochner, ZL, to appear]

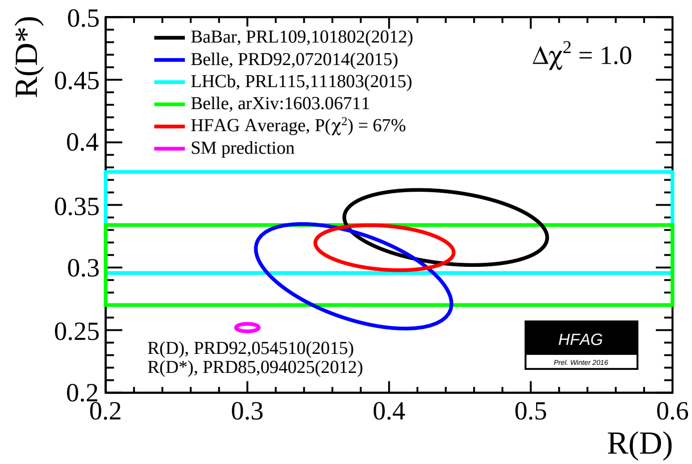
Time permitting...

- One slide on future uncertainty of $\sin 2\beta$ [ZL & Robinson, PRL 115 (2015) 251801, 1507.06671]
- ϵ_K probes highest scales among $\Delta F = 2$, sensitive to many BSM models
  - SM prediction uncertainty $\sim 10\%$ vs. exp. uncertainty $\sim 0.5\%$ [ZL, F. Sala, 1602.08494]

The most significant deviation from the SM

- Belle & LHCb results on the anomaly seen by BaBar in $R(X) = \dfrac{\Gamma(B \to X\tau\bar\nu)}{\Gamma(B \to X(e/\mu)\bar\nu)}$

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
Belle		$0.302 \pm 0.030 \pm 0.011$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.397 ± 0.049	0.316 ± 0.019
my SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



SM predictions fairly robust: heavy quark symmetry + lattice QCD, only $R(D)$ [1503.07237, 1505.03925]

- Next: LHCb result for $R(D)$? Use more τ decays? $\Lambda_b \to \Lambda_c^{(*)}\tau\nu$? $B_s \to D_s^{(*)}\tau\nu$?

- Need NP at fairly low scales (leptoquarks, W', etc.), likely visible in LHC Run 2

- Question we asked: can MFV new physics explain the data?

SM predictions fairly robust

- Measurements + heavy quark symmetry + lattice QCD

  All form factors = Isgur-Wise function + $\mathcal{O}(\Lambda_{\rm QCD}/m)$ corrections

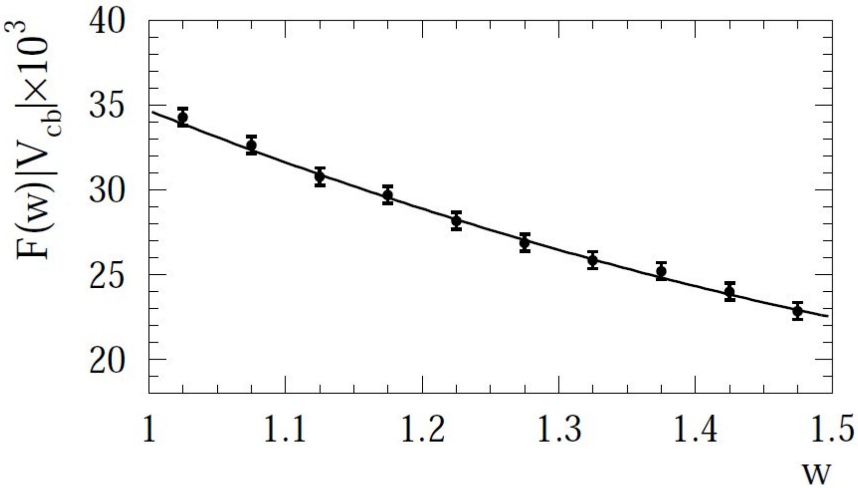
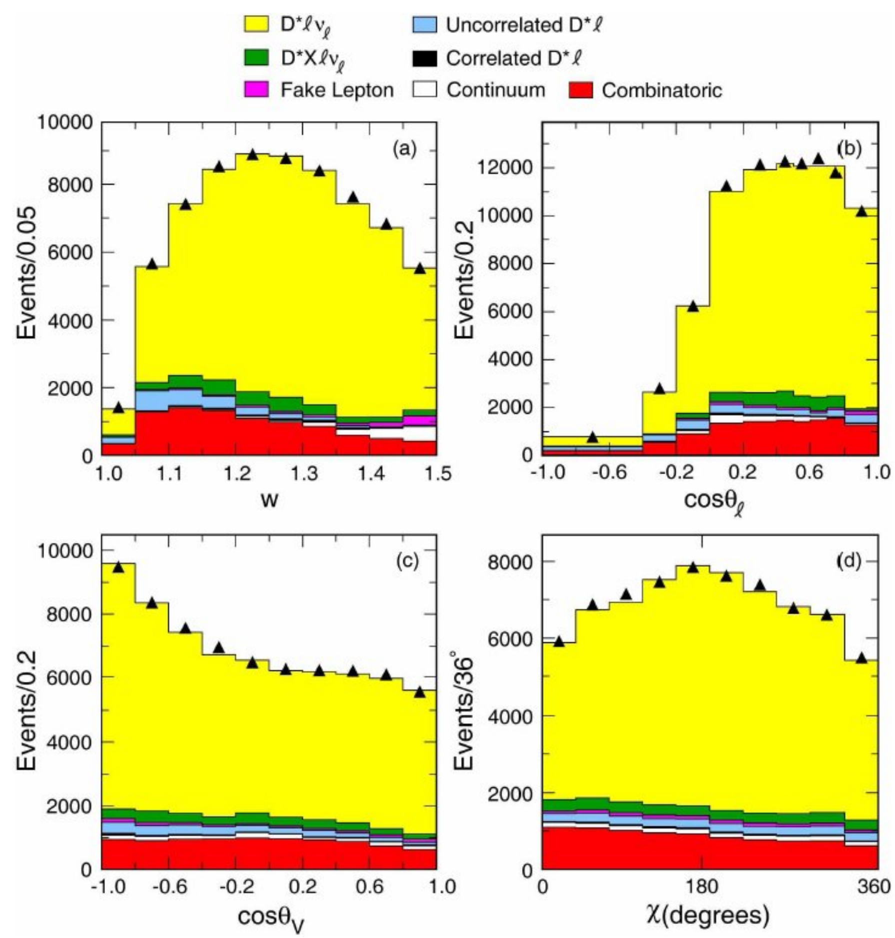


FIG. 6: The measured w dependence of $\mathcal{F}(w)|V_{cb}|$ (data points) compared to the theoretical function with the fitted parameters (solid line). The experimental uncertainties are too small to be visible.

[BaBar, 0705.4008]



Tension with SM is model independent

- Use OPE for inclusive $B \to X_c \tau \bar{\nu}$ to get model independent constraints on SM
- Learn from inclusive $= \sum$ exclusive

$R(X_c) = 0.222 \pm 0.003$ [Freytsis, ZL, Ruderman, update of earlier results]

$\mathcal{B}(B^- \to X_c \ell \bar{\nu}) = (10.92 \pm 0.16)\%$

Predict: $\mathcal{B}(B^- \to X_c \tau \bar{\nu}) = (2.42 \pm 0.05)\%$
vs. LEP: $\mathcal{B}(b \to X \tau^+ \nu) = (2.41 \pm 0.23)\%$

- The $R(D^{(*)})$ data imply: $\mathcal{B}(\bar{B} \to D^* \tau \bar{\nu}) + \mathcal{B}(\bar{B} \to D \tau \bar{\nu}) = (2.78 \pm 0.25)\%$
- SM estimate $\mathcal{B}(B \to D^{**} \tau \bar{\nu}) \gtrsim 0.15\%$ (four $1P$ states) details later
- Tension $\gtrsim 2\sigma$, based on calculation of SM inclusive rate + minimal assumptions
  Complementary to comparison with SM calculation of $R(D^{(*)})$

Operator analysis

Consider redundant set of operators

- Fits to different fermion orderings convenient to understand allowed mediators

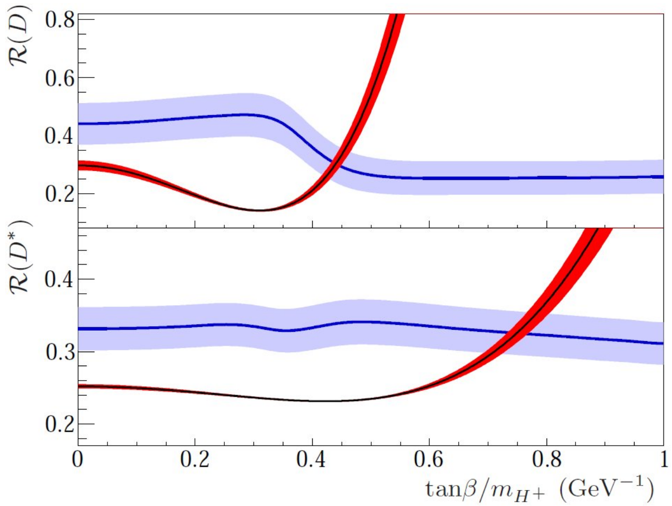
Usually only the first 5 operators considered, related by Fierz

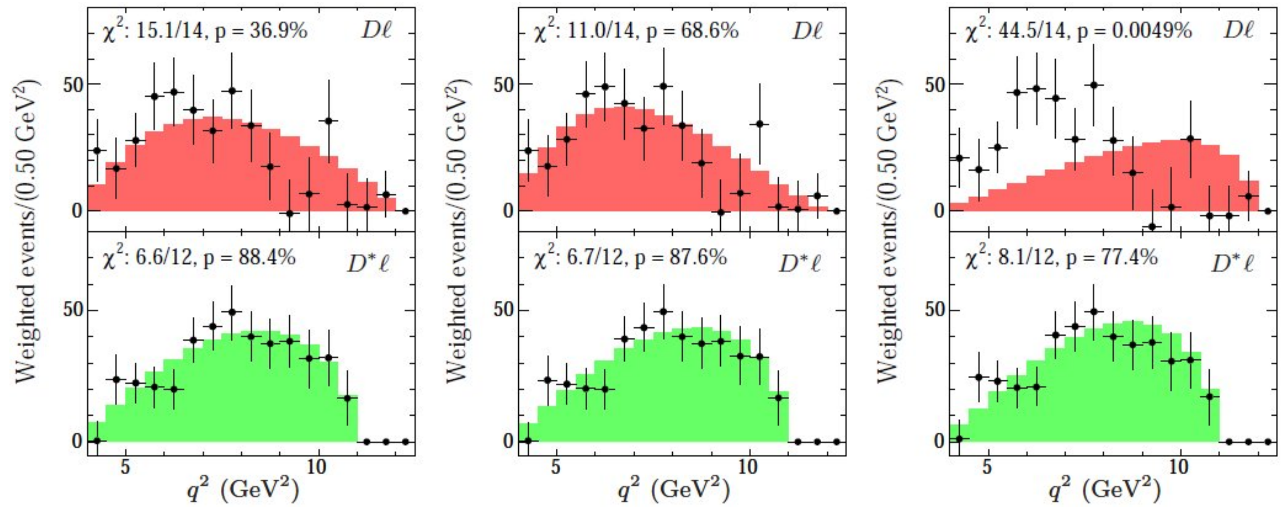
from dim-6 terms, others from dim-8 only $\Downarrow$

	Operator		Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L\nu)$			$(1,3)_0$	$(g_q\bar{q}_L\boldsymbol{\tau}\gamma^\mu q_L + g_\ell\bar{\ell}_L\boldsymbol{\tau}\gamma^\mu\ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L\nu)$				
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L\nu)$			$\rangle (1,2)_{1/2}$	$(\lambda_d\bar{q}_L d_R\phi + \lambda_u\bar{q}_L u_R i\tau_2\phi^\dagger + \lambda_\ell\bar{\ell}_L e_R\phi)$
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L\nu)$				
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu)$				
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L\nu)$	$\longleftrightarrow$	$\mathcal{O}_{V_L}$ $\langle$	$(3,3)_{2/3}$	$\lambda\,\bar{q}_L\boldsymbol{\tau}\gamma_\mu\ell_L\boldsymbol{U}^\mu$
				$\rangle (3,1)_{2/3}$	$(\lambda\,\bar{q}_L\gamma_\mu\ell_L + \tilde{\lambda}\,\bar{d}_R\gamma_\mu e_R)U^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L\nu)$	$\longleftrightarrow$	$-2\mathcal{O}_{S_R}$		
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L\nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L\nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(3,2)_{7/6}$	$(\lambda\,\bar{u}_R\ell_L + \tilde{\lambda}\,\bar{q}_L i\tau_2 e_R)R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L b)\,(\bar{c}\sigma_{\mu\nu}P_L\nu)$	$\longleftrightarrow$	$-6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L\nu)$	$\longleftrightarrow$	$-\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L\nu)$	$\longleftrightarrow$	$-2\mathcal{O}_{S_R}$	$(\bar{3},2)_{5/3}$	$(\lambda\,\bar{d}^c_R\gamma_\mu\ell_L + \tilde{\lambda}\,\bar{q}^c_L\gamma_\mu e_R)V^\mu$
				$(\bar{3},3)_{1/3}$	$\lambda\,\bar{q}^c_L i\tau_2\boldsymbol{\tau}\ell_L\boldsymbol{S}$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L\nu)$	$\longleftrightarrow$	$\frac{1}{2}\mathcal{O}_{V_L}$ $\langle$		
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L\nu)$	$\longleftrightarrow$	$-\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$\rangle (\bar{3},1)_{1/3}$	$(\lambda\,\bar{q}^c_L i\tau_2\ell_L + \tilde{\lambda}\,\bar{u}^c_R e_R)S$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu}P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu}P_L\nu)$	$\longleftrightarrow$	$-6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

BaBar statements from q^2 spectrum results

- BaBar studied consistency of rates with 2HDM, and $\mathrm{d}\Gamma/\mathrm{d}q^2$ with several models



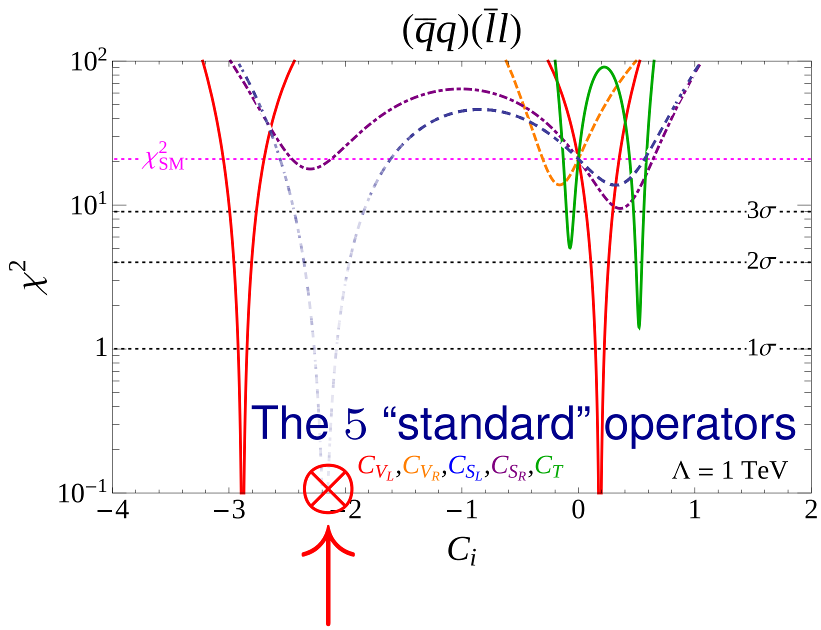


[PRL 109 (2012) 101802, arXiv:1205.5442]

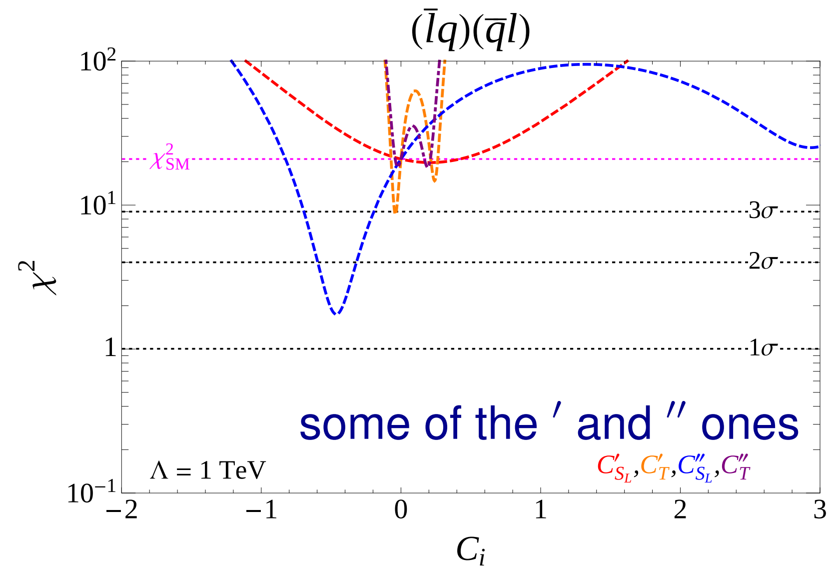
[PRD 88 (2013) 072012, arXiv:1303.0571]

- Found that type-II 2HDM gave nearly as bad fit to the data as the SM
- $\mathrm{d}\Gamma/\mathrm{d}q^2$ has additional discriminating power (no other distribution measured yet)
- No public info on bin-to-bin correlations, eyeball which solutions are (dis)favored

Fits to a single operator



[BaBar, 1303.0571]



Solution marked $\otimes$ ruled out by the q^2 spectrum

- In HQET limit, we confirmed "classic" paper (one minor typo) [Goldberger, hep-ph/9902311]
- Large coefficients, $\Lambda = 1\,\text{TeV}$ in plots $\Rightarrow$ fairly light mediators (obvious: 20–30% of a tree-level rate)

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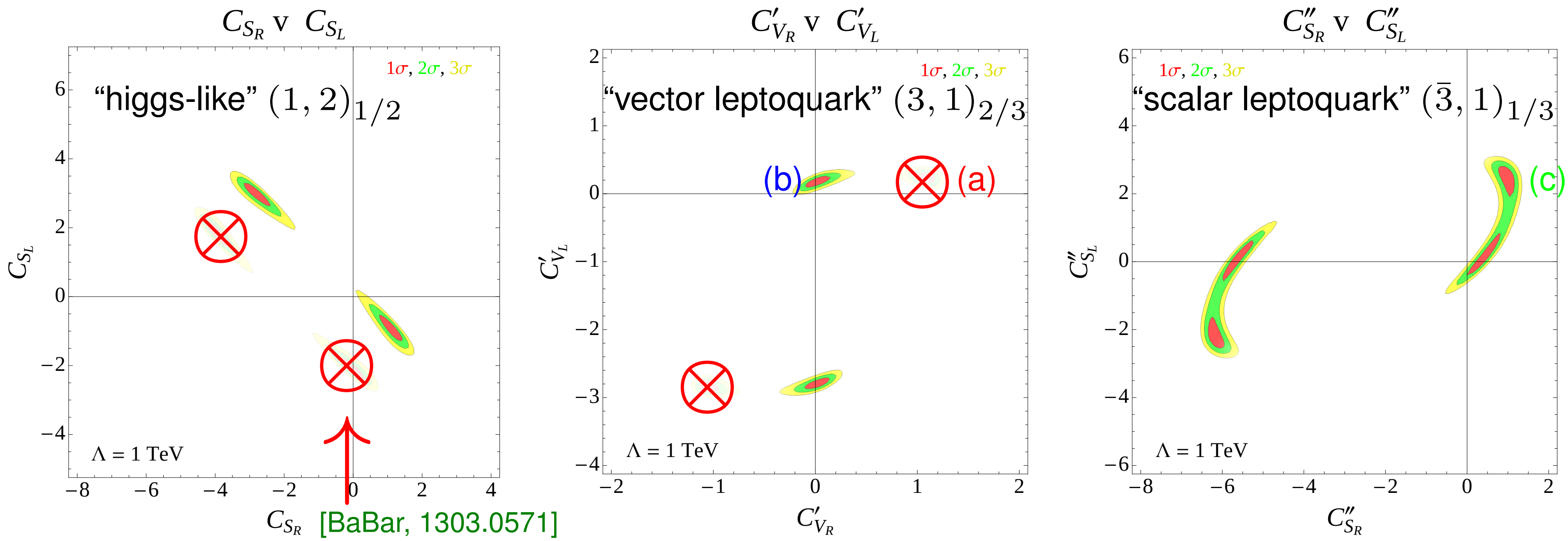
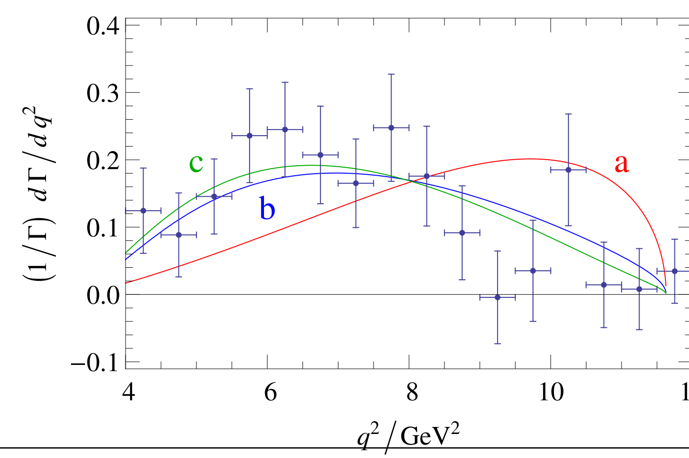
Fits to two operators



Solution marked ⊗ ruled out by the q^2 spectrum

Operator coefficients	
$C'_{V_L} = 0.24$	$C'_{V_R} = 1.10$
$C'_{V_L} = 0.18$	$C'_{V_R} = -0.01$
$C''_{S_R} = 0.96$	$C''_{S_L} = 2.41$



Operator fits → viable / sensible models

- Good fits for several mediators: scalar, "Higgs-like" $(1,2)_{1/2}$
  vector, "W'-like" $(1,3)_0$
  "scalar leptoquark" $(\bar{3},1)_{1/3}$ or $(\bar{3},3)_{1/3}$
  "vector leptoquark" $(3,1)_{2/3}$ or $(3,3)_{2/3}$

- If there is NP within reach, its flavor structure must be highly non-generic
  Surprising if only BSM operator had $(\bar{b}c)(\bar{\tau}\nu)$ structure

- Minimal flavor violation (MFV) is probably a useful starting point
  Global $U(3)_Q \times U(3)_u \times U(3)_d$ flavor sym. broken by $Y_u \sim (\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $Y_d \sim (\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$

- Which BSM scenarios can be MFV? [Freytsis, ZL, Ruderman, 1506.08896]
  Not scalars, nor vectors, possibly viable LQ: scalar $S(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$ or vector $U_\mu(\mathbf{1},\mathbf{1},\mathbf{3})$

  Bounds: $b \to s\nu\bar{\nu}$, D^0 & K^0 mixing, $Z \to \tau^+\tau^-$, LHC contact int., $pp \to \tau^+\tau^-$, etc.

Survey of MFV model

- Scalars: Need $C_{S_L}/C_{S_R} \sim \mathcal{O}(1)$
  Hard to avoid y_c suppression or $\mathcal{O}(1)$ coupling to 1st generation
- Vectors: Rescaling the SM operator (O_{V_L}) gives good fit to the data
  Flavor singlet excluded by LHC, simplest charges don't work w/o assumptions
  If dynamics allows $W'\bar{Q}_L^3 Q_L^3$, but not $W'\bar{Q}_L^i Q_L^i$, viable models exist; beyond MFV [Greljo, Isidori, Marzocca, 1506.0170]

- Leptoquarks: Viable MFV models exist

  Simplest choices — leptoquarks could be electroweak $SU(2)_L$ singlets or triplets:

  scalars: $S \sim (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})\,, \quad (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{1})\,, \quad (\mathbf{1}, \mathbf{1}, \bar{\mathbf{3}})$

  vectors: $U_\mu \sim (\mathbf{3}, \mathbf{1}, \mathbf{1})\,, \quad (\mathbf{1}, \mathbf{3}, \mathbf{1})\,, \quad (\mathbf{1}, \mathbf{1}, \mathbf{3})$
- Possibly viable: $S(\mathbf{1}, \mathbf{1}, \bar{\mathbf{3}})$ and $U_\mu(\mathbf{1}, \mathbf{1}, \mathbf{3}) \Rightarrow$ consider in more detail

  Both can be electroweak singlets or triplets

The $S(1,1,\bar{3})$ scalar LQ

- Interactions terms for electroweak singlet:

$$\mathcal{L} = S(\lambda Y_d^\dagger\, \bar{q}_L^c i\tau_2 \ell_L + \tilde{\lambda} Y_d^\dagger Y_u\, \bar{u}_R^c e_R)$$
$$= S_i(\lambda y_{d_i} V_{ji}^*\, \bar{u}_{Lj}^c e_L - \lambda y_{d_i} \bar{d}_{Li}^c \nu_L + \tilde{\lambda} y_{d_i} y_{u_j} V_{ji}^*\, \bar{u}_{Rj}^c e_R)$$

Integrating out S, contribution to $R(X_c)$ via: $(m_{S_3} \neq m_{S_1} = m_{S_2})$

$$-\frac{V_{cb}^*}{m_{S_3}^2}\Big(\lambda^2 y_b^2\, \mathcal{O}''_{S_R} + \lambda\tilde{\lambda} y_c y_b^2\, \mathcal{O}''_{S_L}\Big)$$

[electroweak triplet has no $\tilde{\lambda}$ term]

- Can fit $R(D^{(*)})$ data if $y_b = \mathcal{O}(1)$ Check $Z\tau^+\tau^-$ constraints, etc.
- Leptons: (i) τ alignment, charge LQ and 3rd gen. leptons opposite under $U(1)_\tau$
  (ii) lepton MFV, $(\mathbf{1},\bar{\mathbf{3}})$ under $U(3)_L \times U(3)_e$ [constraints differ]
- LHC Run 1 bounds on pair-produced LQ decaying to $t\tau$ or $b\nu$, $m_{S_3} \gtrsim 560\,\text{GeV}$

Many signals, tests, consequences

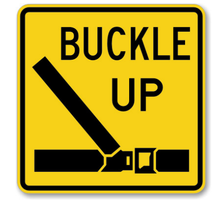
- LHC: several extensions to current searches would be interesting
  - Extend $\tilde{t}$ and $\tilde{b}$ searches to higher prod. cross section
  - Search for $t \to b\tau\bar{\nu}$, $c\tau^+\tau^-$ nonresonant decays
  - Search for states on-shell in t-channel, but not in s-channel
  - Search for $t\tau$ resonances

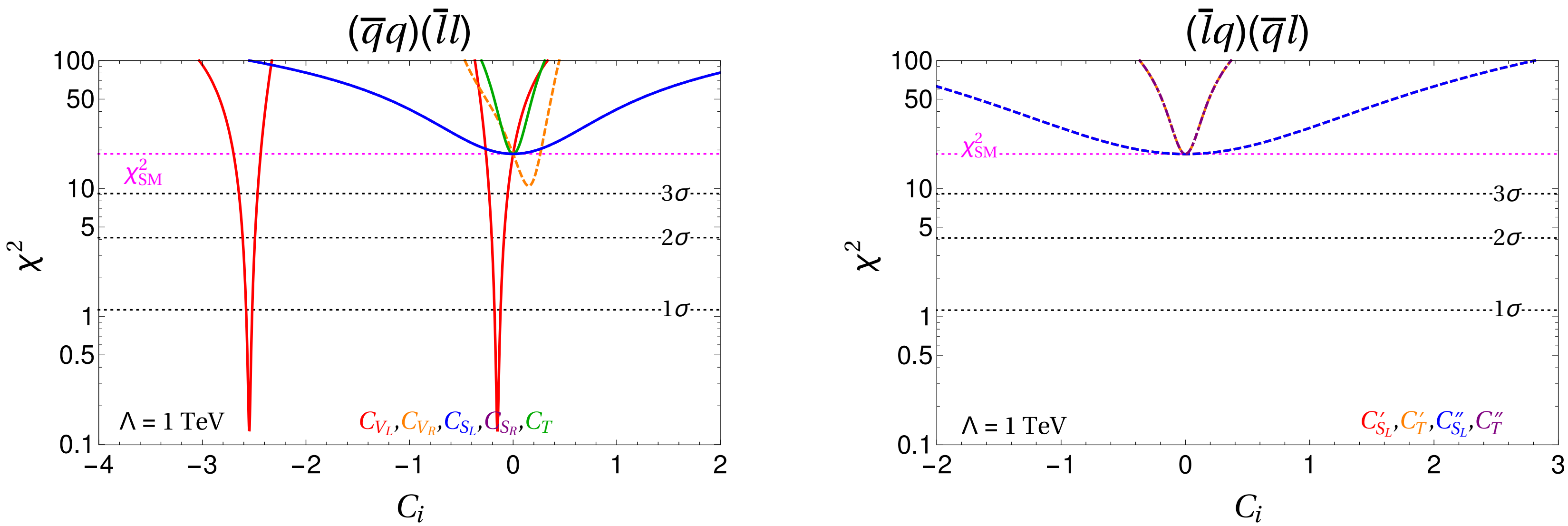
- Low energy probes:
  - Firm up $B \to D^{(*)}\tau\bar{\nu}$ rate and kinematic distributions; Cross checks w/ inclusive
  - Smaller theor. error in $[\mathrm{d}\Gamma(B \to D^{(*)}\tau\bar{\nu})/\mathrm{d}q^2]/[\mathrm{d}\Gamma(B \to D^{(*)}l\bar{\nu})/\mathrm{d}q^2]$ at same q^2
  - Improve bounds on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$
  - $\mathcal{B}(D \to \pi\nu\bar{\nu}) \sim 10^{-5}$ possible, maybe BES III; enhanced $\mathcal{B}(D \to \mu^+\mu^-)$
  - $\mathcal{B}(B_s \to \tau^+\tau^-) \sim 10^{-3}$ possible

How strange models might be viable?

- All papers enhance the τ mode compared to the SM

  Can one suppress the e and μ modes instead?





- Viable option: modify the SM four-fermion operator

Good fit with: $V_{cb}^{(\rm exp)} \sim V_{cb}^{(\rm SM)} \times 0.9 \qquad V_{ub}^{(\rm exp)} \sim V_{ub}^{(\rm SM)} \times 0.9$

What about $e - \mu$ (non)universality?

- How well is the difference of the e and μ rates constrained?

Parameters	De sample	$D\mu$ sample	combined result
ρ_D^2	$1.22 \pm 0.05 \pm 0.10$	$1.10 \pm 0.07 \pm 0.10$	$1.16 \pm 0.04 \pm 0.08$
$\rho_{D^*}^2$	$1.34 \pm 0.05 \pm 0.09$	$1.33 \pm 0.06 \pm 0.09$	$1.33 \pm 0.04 \pm 0.09$
R_1	$1.59 \pm 0.09 \pm 0.15$	$1.53 \pm 0.10 \pm 0.17$	$1.56 \pm 0.07 \pm 0.15$
R_2	$0.67 \pm 0.07 \pm 0.10$	$0.68 \pm 0.08 \pm 0.10$	$0.66 \pm 0.05 \pm 0.09$
$\mathcal{B}(D^0 \ell \overline{\nu})(\%)$	$2.38 \pm 0.04 \pm 0.15$	$2.25 \pm 0.04 \pm 0.17$	$2.32 \pm 0.03 \pm 0.13$
$\mathcal{B}(D^{*0} \ell \overline{\nu})(\%)$	$5.50 \pm 0.05 \pm 0.23$	$5.34 \pm 0.06 \pm 0.37$	$5.48 \pm 0.04 \pm 0.22$
χ^2/n.d.f. (probability)	416/468 (0.96)	488/464 (0.21)	2.0/6 (0.92)

[BaBar, 0809.0828 — similar results in Belle, 1010.5620]

- 10% difference allowed... wrong statements...

Γ_1	$e^+ \nu_e$ anything	$(10.86 \pm 0.16)\%$
Γ_2	$\overline{p} e^+ \nu_e$ anything	$< 5.9 \times 10^{-4}$
Γ_3	$\mu^+ \nu_\mu$ anything	$(10.86 \pm 0.16)\%$
Γ_4	$\ell^+ \nu_\ell$ anything	$(10.86 \pm 0.16)\%$

- Can difference be constrained better? How much better?

  Reaching the 1% level on ratio might be possible (but challenging) at Belle II

Not excluded?

- LQ pair production
- top decays
- t-channel non-resonant l^+l^- production
- LEP $Z \to l^+l^-$, HERA LQ production
- $c\bar{c}e^+e^-$ contact interaction / compositness

- $B - \overline{B}$ mixing, $K - \overline{K}$ mixing, $D - \overline{D}$ mixing
- $B \to X_s \nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$
- $D \to l^+l^-$ at tree level
- $B^- \to \mu\bar{\nu}$ at tree level
- $B_s \to \mu^+\mu^-$ and $K_L \to \mu^+\mu^-$ at one loop

- Strongest constraint from ϵ_K:

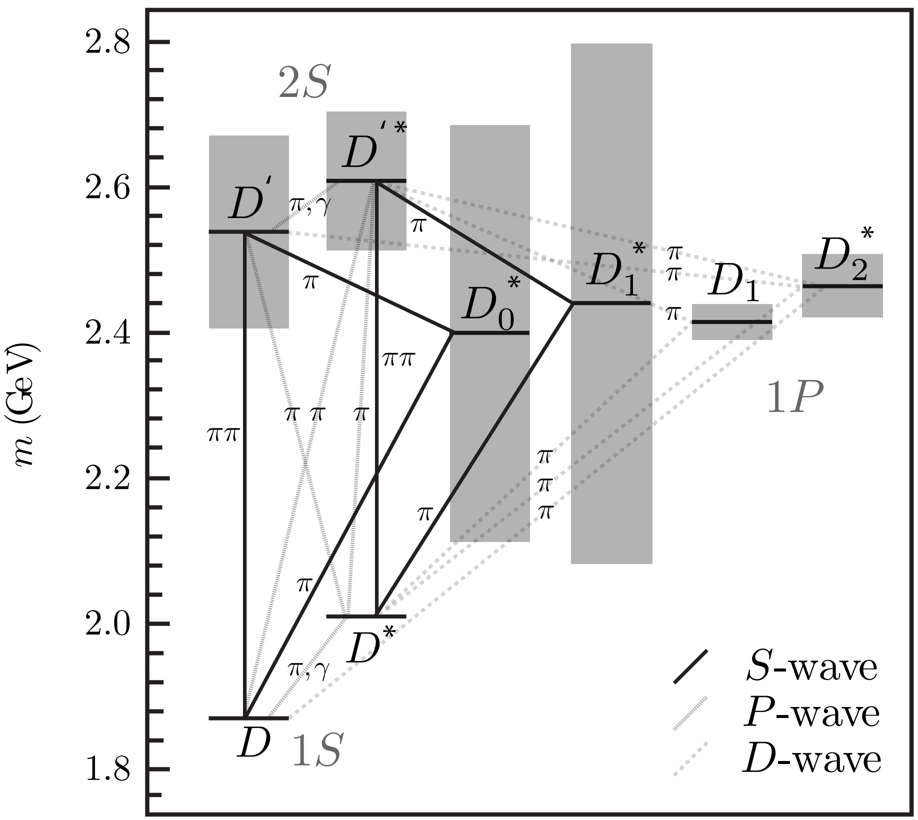
$$|\epsilon_K|_{\rm SM} = \frac{G_F^2\, m_W^2\, m_K f_K^2}{6\sqrt{2}\,\pi^2\,\Delta m_K}\, \hat{B}_K\, \kappa_\epsilon |V_{cb}|^2\, \lambda^2\, \bar{\eta} \Big[|V_{cb}|^2 (1-\bar{\rho})\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \Big]$$

$|\epsilon_K|_{\rm exp} = (2.23 \pm 0.01) \times 10^{-3}$ vs. $|\epsilon_K|_{\rm SM} = (1.81 \pm 0.28) \times 10^{-3}$ [Brod & Gorbahn, 2011]

  – Uncertainties big enough to allow for $5-10\%$ enhancement of $|V_{cb}|$
  – The $R(D^{(*)})$ excess may shrink and be significant; can also make cocktails...

- Even an enhancement much smaller than today can become 5σ in the future

$B \to D^{**}\tau\bar{\nu}$



Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2320	265
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

Why bother...?

- $B \to D^{**}\tau\bar\nu$: rates to narrow D_1, D_2^* measurable? No predictions [Bernlochner, ZL, soon]

  In $B_s \to D_s^{**}\ell\bar\nu$ case, all 4 D_s^{**} states are narrow $\Rightarrow$ LHCb?

- Largest systematic uncertainty
- May matter for tensions between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations
- Complementary sensitivity to NP
- Complementary experimentally
- Decay rates not prohibitively small

	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio $f_{\rm wc}$	0.0	0.0	0.84
$M^2_{\rm miss}$ shape	0.6	1.0	0.00
$o'_{\rm NB}$ shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	-0.32

[Belle, 1507.03233]

Some model independent results

- At $w \equiv v \cdot v' = 1$, the $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ matrix element is determined by masses and leading order Isgur-Wise function [Leibovich, Ligeti, Stewart, Wise, hep-ph/9703213, hep-ph/9705467]

  Kinematic range: $1 \le w \lesssim 1.3$ and in the τ case $1 \le w \lesssim 1.2$

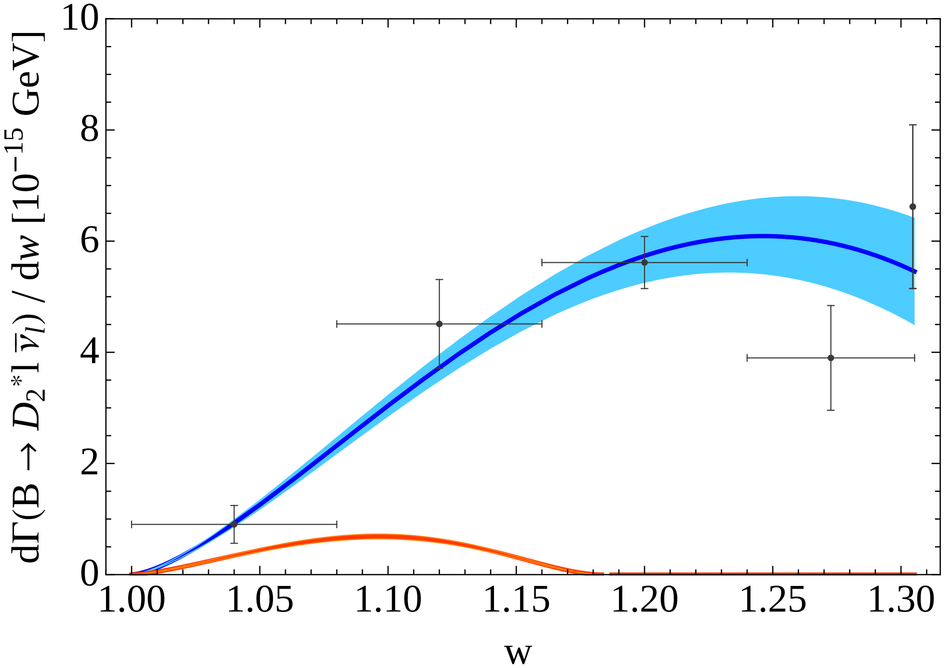
  Meson masses: $$m_{H_\pm} = m_Q + \bar\Lambda^H - \frac{\lambda_1^H}{2m_Q} \pm \frac{n_\mp \lambda_2^H}{2m_Q} + \ldots \qquad n_\pm = 2J_\pm + 1$$

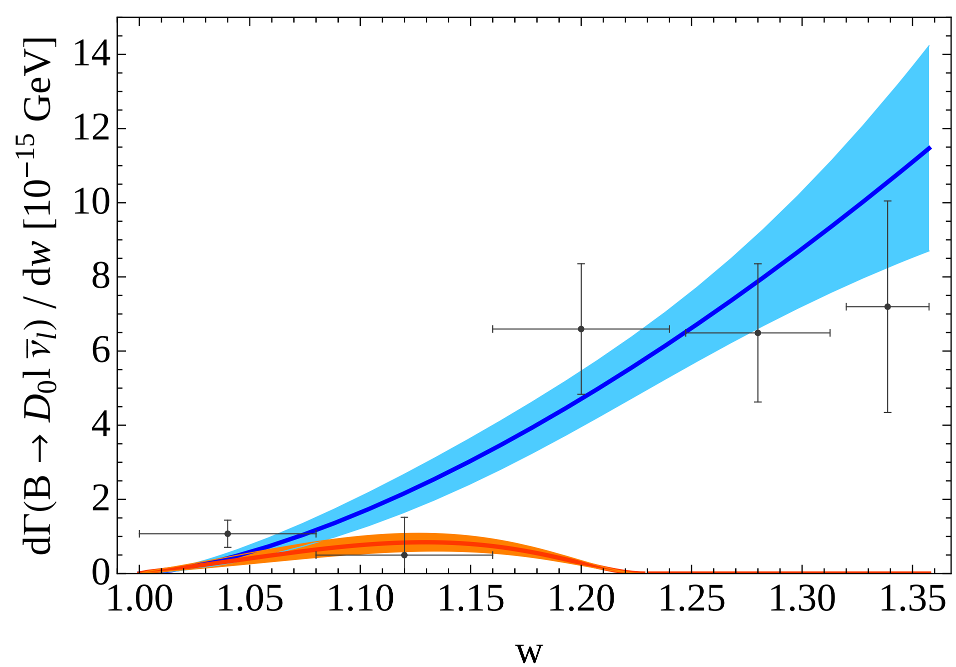
  For example:
  $$\frac{\langle D_1(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_1}\, m_B}} = f_{V_1} \epsilon^{*\mu} + (f_{V_2} v^\mu + f_{V_3} v'^\mu)(\epsilon^* \cdot v)$$
  $$\sqrt{6}\, f_{V_1}(w) = (1-w^2)\,\tau(w) - 4\,\frac{\bar\Lambda' - \bar\Lambda}{m_c}\,\tau(w) + \mathcal{O}\left(\frac{w-1}{m_{c,b}}\right) + \ldots$$

- These "known" $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ terms are numerically very important

- No expressions in the literature for $B \to D^{**}\,\tau\bar\nu$ rates at all — fixing this...

Preliminary predictions of spectra



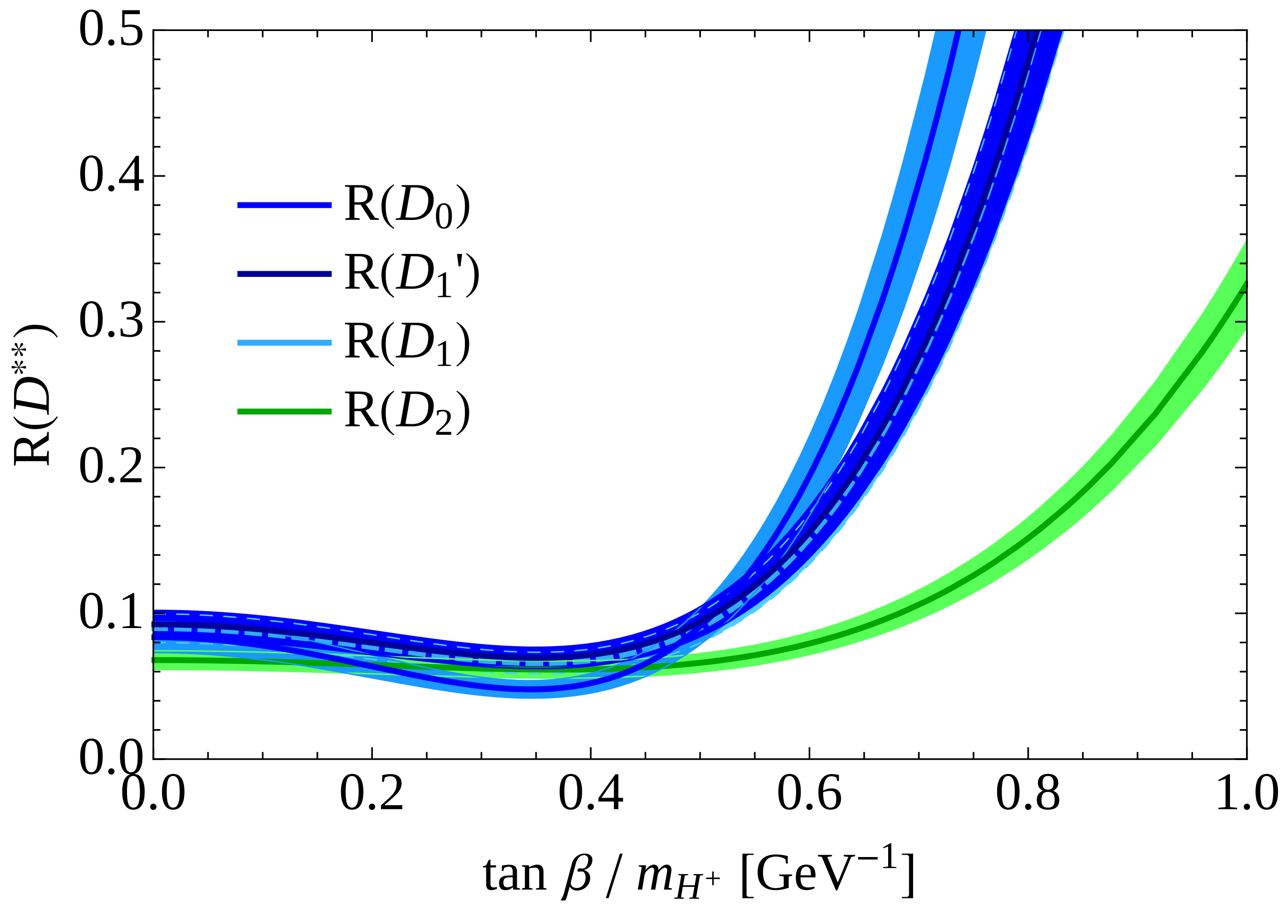


Rates for e, μ vs. τ

[Data from Belle, 0711.3252]

- Study all uncertainties, including effects neglected in LLSW
- As for $B \to D^{(*)}\ell\bar{\nu}$, heavy quark symmetry relates the extra form factor in the τ mode to those with e, μ — finalizing the uncertainties

Complementary sensitivity — e.g., type-II 2HDM



- 2HDM just for illustration — explore influence of all possible non-SM operators

Theory uncertainty of $\sin 2\beta$

$SU(3)$ and the uncertainty in $\sin 2\beta$

- Hadronic uncertainty: $|V_{ub}V_{us}/(V_{cb}V_{cs})| \times (\text{“}P/T\text{”}) \simeq 0.02 \times$ (ratio of matrix elem.)

  Claims of large effects, many proposals, encouraging experimental bounds

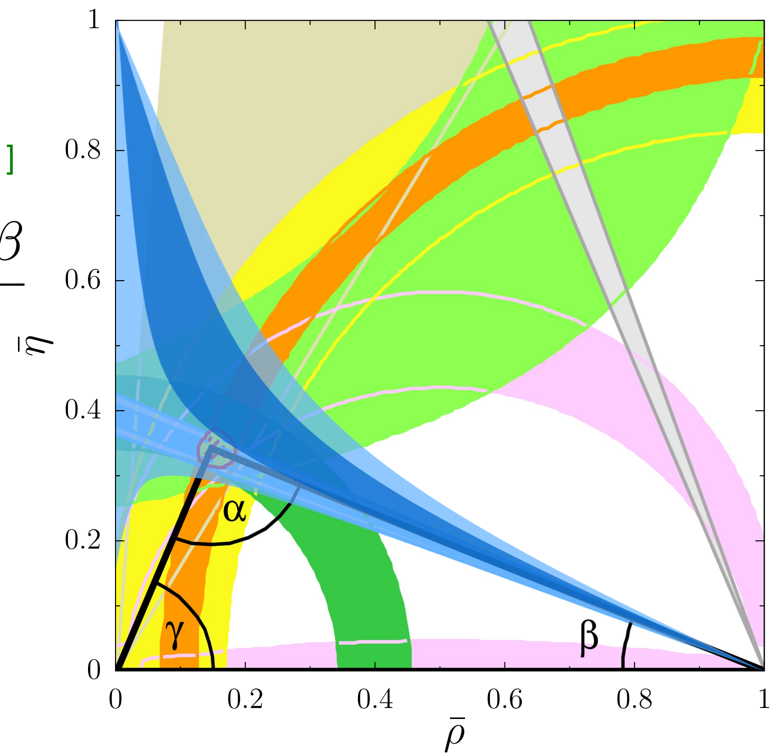
  Diagrammatic assumptions, sizes of matrix elements; e.g., no $SU(3)$ rel. btw $B_s \to \psi\phi$ and $\psi\rho$

- An $SU(3)$ relation, w/o dynamical assumptions

  [ZL & Robinson, PRL 115 (2015) 251801, 1507.06671]

$$\sin 2\beta = \frac{S_{K_S} - \lambda^2 S_{\pi^0} - 2(\Delta_K + \lambda^2 \Delta_\pi) \tan\gamma \cos 2\beta}{1+\lambda^2}$$

$$\Delta_{h=K,\pi} = \frac{\bar\Gamma(B_d \to J/\psi h^0) - \bar\Gamma(B^+ \to J/\psi h^+)}{\bar\Gamma(B_d \to J/\psi h^0) + \bar\Gamma(B^+ \to J/\psi h^+)}$$



- Cancels $|V_{ub}|$ contamination in $SU(3)$ limit

  Challenge: measuring $\Delta_{K,\pi}$ [Jung, 1510.03423]

- 2σ tension: fluctuation in $\Delta_K = -(4.3 \pm 2.4) \times 10^{-2}$? isospin violation?

Theory uncertainty of ϵ_K

[ZL, F. Sala, 1602.08494]

Very high scale sensitivity

- ϵ_K has played a leading role constraining both general and specific models

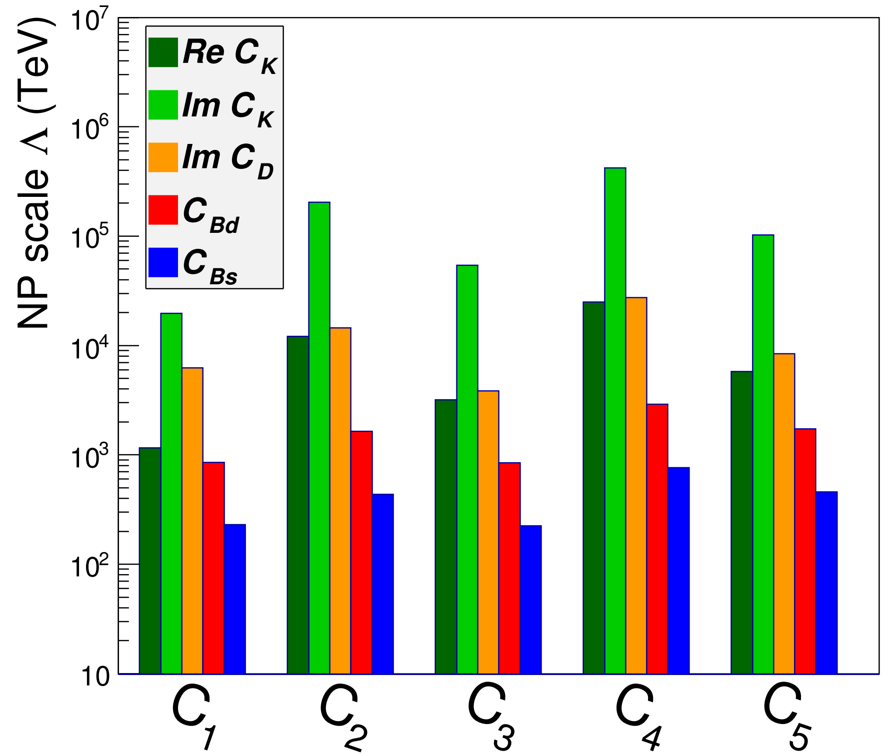
$$|\epsilon_K|_{\rm exp} = (2.23 \pm 0.01) \times 10^{-3} \quad \text{vs.} \quad |\epsilon_K|_{\rm SM} = (1.81 \pm 0.28) \times 10^{-3}$$ [Brod & Gorbahn, 2011]

- Besides SM operator, $O_1 = (\bar{d}_L \gamma_\mu s_L)^2$ four others possible:

$$O_2 = (\bar{d}_R s_L)^2, \quad O_3 = (\bar{d}_R^\alpha s_L^\beta)(\bar{d}_R^\beta s_L^\alpha),$$
$$O_4 = (\bar{d}_R s_L)(\bar{d}_L s_R), \quad O_5 = (\bar{d}_R^\alpha s_L^\beta)(\bar{d}_L^\beta s_R^\alpha)$$

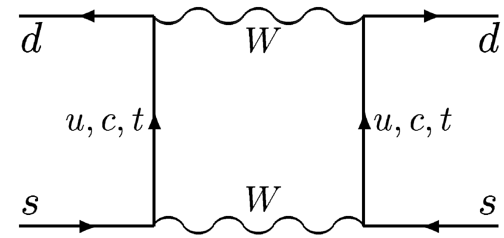
$$\mathcal{L}_{\rm NP} = \mathcal{L}_{\rm SM} + \sum_j \frac{C_j}{\Lambda_j^2} O_i$$

ϵ_K give the strongest $\Delta F = 2$ constraint
(Plot for ${\rm Im}C_K$ shows Λ_j for $C_j = i$)



ϵ_K — convention independently

- $|K_{S,L}\rangle = p|K^0\rangle \pm q|\overline{K}^0\rangle \qquad K_L = K_{\text{heavy}}\,, \quad K_S = K_{\text{light}}$



Time evolution: $i\,\dfrac{d}{dt}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} = \left(M - i\,\dfrac{\Gamma}{2}\right)\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix}$

$$\Delta m_K = 2|M_{12}| + \mathcal{O}(\phi^2)\,, \qquad \Delta\Gamma_K = -2|\Gamma_{12}| + \mathcal{O}(\phi^2)$$

- Fully convention independently:

$$\epsilon_K = e^{i\phi_\epsilon}\sin\phi_\epsilon\,\frac{\mathrm{Im}(-M_{12}/\Gamma_{12})}{2\,|M_{12}/\Gamma_{12}|} + \mathcal{O}\left(\epsilon_K^2, |\epsilon'|\right) \qquad \phi_\epsilon = \arctan\frac{2\,\Delta m_K}{-\Delta\Gamma_K} \simeq 43.5^\circ$$

- Usually written as: $\epsilon_K = e^{i\phi_\epsilon}\sin\phi_\epsilon\left(\dfrac{\mathrm{Im}M_{12}}{\Delta m_K} + \xi\right) \qquad \xi = \dfrac{\mathrm{Im}(A_0\,e^{-i\delta_0})}{\mathrm{Re}(A_0\,e^{-i\delta_0})}$

(since Γ_{12} dominated by A_0 because of $\Delta I = 1/2$ rule)

Valid in phase conventions: $\{\arg M_{12}\,,\ \arg\Gamma_{12}\} \leq \mathcal{O}(|\epsilon_K|)$ (mod π)

Calculating ϵ_K

- The standard expression for the SM prediction:

$$|\epsilon_K| = \kappa_\epsilon C_\epsilon \widehat{B}_K |V_{cb}|^2 \lambda^2 \,\bar\eta \left[|V_{cb}|^2 (1-\bar\rho)\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_t, x_c) - \eta_{cc} x_c \right]$$

$75(1)\%$ (NLO) $\quad 43(6)\% \quad -18(7)\%$ (NNLO)

Poor convergence of η_{cc}: $1,\ 1.38,\ 1.87 \;\Rightarrow\; \eta_{cc} = 1.87 \pm 0.76$ [Brod, Gorbahn 1108.2036]

- κ_ϵ include all contributions other than the short-distance $\Delta s = 2$

$$\kappa_\epsilon = \sqrt{2}\, \sin\phi_\epsilon \left(1 + \rho \frac{\xi}{\sqrt{2}\,|\epsilon_K|} \right) \simeq 0.94 \pm 0.02$$

[Buras, Guadagnoli, Isidori, 1002.3612]

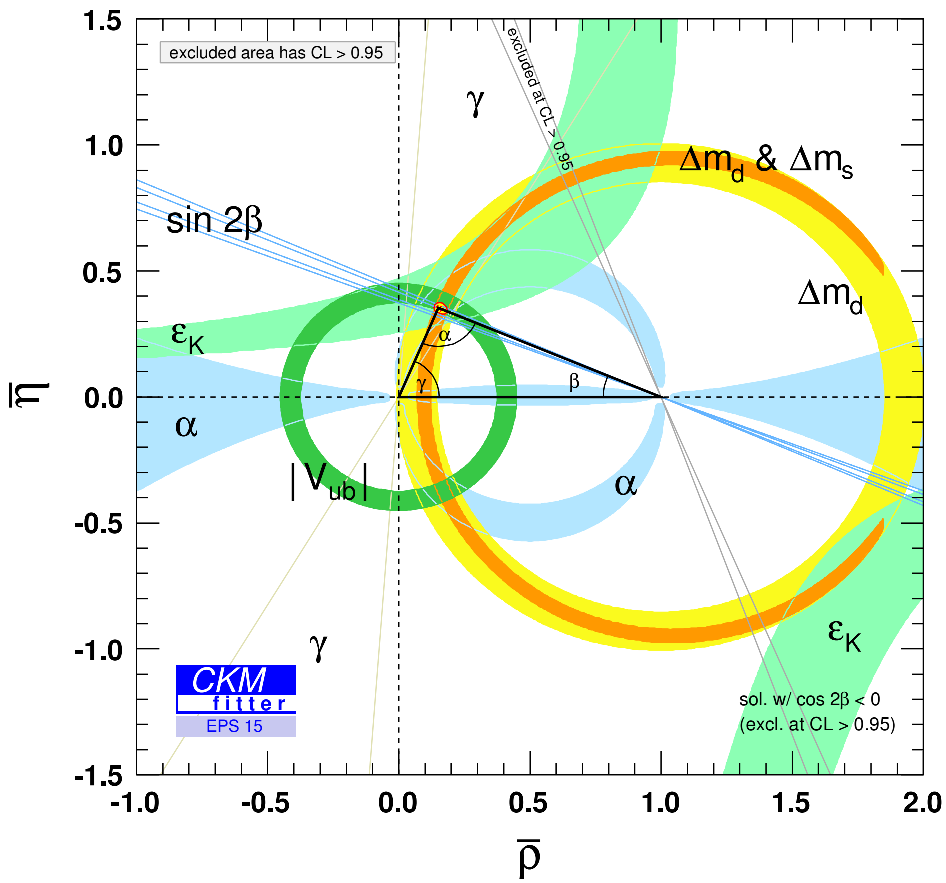
To use or not to use measured ϵ' to predict ϵ_K? What's assumed about NP?

Lattice estimates don't agree well (or NP?) — reflected in tension for ϵ'

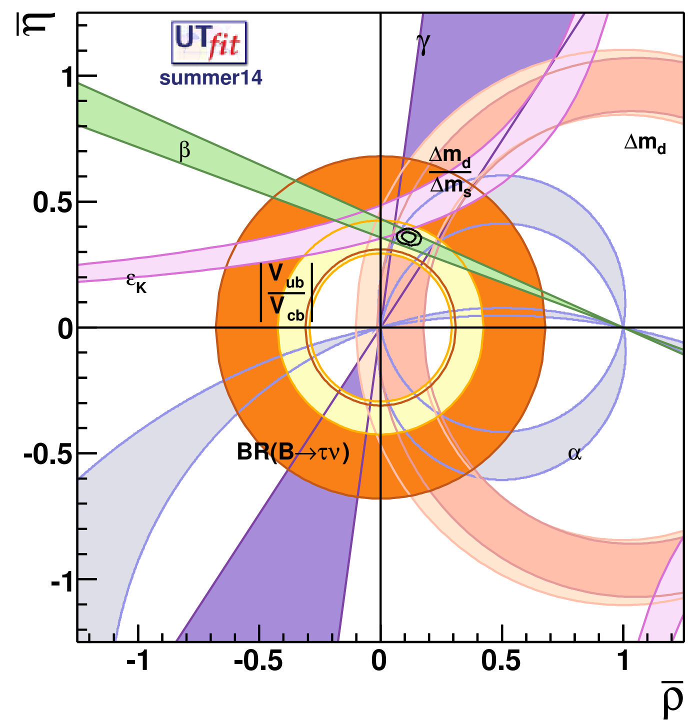
- $(\Delta m_K)^{\rm LD}$ uncertain: importance of 2π state between lattice and χPT in tension

Compare SM CKM fits

- The ϵ_K regions are fairly different (widths of bands):



CKMfitter: η_{cc} @ NNLO



UTfit: η_{cc} @ NLO

Phase choices for M_{12} and Γ_{12}

- Change phases to minimize / study uncertainty in the actual computation?

$$|\epsilon_K|_{\rm new} = \kappa_\epsilon|_{\rm new}\, C_\epsilon \widehat{B}_K |V_{cb}|^2 \lambda^2\, \bar\eta \left[|V_{cb}|^2 (1-\bar\rho)\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_t, x_c)\right]$$

Make $\lambda_c = V_{cd}V_{cs}^*$ real $\Rightarrow$ no η_{cc} term $\Rightarrow$ square bracket increases, κ_ϵ decreases

$\mathrm{Im}M_{12}^{\rm SD}$ increases, κ_ϵ decreases

		η_{cc}	η_{ct}	k_ϵ	m_t	m_c	$\lvert V_{cb}\rvert$	$\bar\eta$	$\bar\rho$	$\lvert\Delta\epsilon_K/\epsilon_K\rvert$
Usual eval.	tree-level inputs	7.3%	4.0%	1.1%	1.7%	0.8 %	11.1%	10.4%	5.4%	18.4%
	SM CKM fit inputs	7.4%	4.0%	1.7%	1.7%	0.8 %	4.2%	2.0%	0.8%	10.1%
Our evaluation	tree-level inputs	—	3.4%	5.2%	1.5%	1.2%	9.5%	8.9%	4.5%	15.6%
	SM CKM fit inputs	—	3.4%	5.9%	1.5%	1.2%	3.6%	1.7%	0.7%	8.3%

- Future: $\Delta|V_{cb}| \to 0.3\times 10^{-3}$, then η_{cc} even more important, $|\Delta\epsilon_K/\epsilon_K|_{V_{cb}} \sim 2.5\%$
- Can this ultimately yield better synergy with lattice QCD calculations?

N.B.: Christ et al. [1212.5931] remove λ_c, to be left with λ_t^2 & $\lambda_t\lambda_u$ terms in $\mathrm{Im}M_{12} \Rightarrow$ then tt part depends on m_c

Final comments

Conclusions

- $B \to D^{(*)}\tau\bar{\nu}$: amusing if NP shows up in an operator w/o much SM suppression
- There are good operator fits, and (somewhat) sensible MFV leptoquark models

  Pretty wild scenarios also viable...
- Extensions of current LHC searches may cover much of the parameter space
- Measurements of $b \to c\tau\bar{\nu}$ will improve in the next decade by order of magnitude

  (Even if central values change, plenty of room for significant deviations from SM)

- ϵ_K: sensitive to some of the highest scales

  Importance of uncertainties of η_{cc} somewhat overlooked — can be “removed”

  $\Delta\epsilon_K|_{\rm SM}$ slightly reduced — Future: understand LD contributions better? Synergy w/ lattice?

Bonus slides

Excluding MFV scalars and vectors

- Scalars: Need comparable values of C_{S_L} and C_{S_R}

  If $H^\pm$ flavor singlet, $C_{S_L} \propto y_c$, so cannot fit $R(D^{(*)})$ keeping y_t perturbative

  If $H^\pm$ is charged under flavor (combination of Y-s, to couple to quarks & leptons), to generate $C_{S_L} \sim C_{S_R}$, some $\mathcal{O}(1)$ coupling to 1st generation quarks unavoidable
  Bounds on $4q$ or $2q2\ell$ operators exclude it

- Vectors: Rescaling the SM operator (O_{V_L}) gives good fit to the data

  Flavor singlet w/ W-like couplings: $m_{W'} \gtrsim 1.8\,\text{TeV} \iff 0.2 \sim g^2|V_{cb}|(1\,\text{TeV}/m_{W'})^2$

  Couplings to u, d suppressed for $(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1})$ and $(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})$ under $U(3)_Q \times U(3)_u \times U(3)_d$
  $(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1})$: $b \to c$ transitions suppressed by y_c, too small
  $(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})$: can fit data if $y_b = \mathcal{O}(1)$, but excluded by tree-level FCNC via W'^0

  (If dynamics allows $W'\bar{Q}_L^3 Q_L^3$, but not $W'\bar{Q}_L^i Q_L^i$, viable models exist; beyond MFV [Greljo, Isidori, Marzocca, 1506.0170])

MFV leptoquarks

- Assign charges under flavor sym.: [viable MFV LQs: Freytsis, ZL, Ruderman]

$$U(3)_Q \times U(3)_u \times U(3)_d$$

- Simplest choices — leptoquarks could be electroweak $SU(2)_L$ singlets or triplets:

$$\text{scalars: } S \sim (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})\,, \quad (\mathbf{1}, \bar{\mathbf{3}}, \mathbf{1})\,, \quad (\mathbf{1}, \mathbf{1}, \bar{\mathbf{3}})$$

$$\text{vectors: } U_\mu \sim (\mathbf{3}, \mathbf{1}, \mathbf{1})\,, \quad (\mathbf{1}, \mathbf{3}, \mathbf{1})\,, \quad (\mathbf{1}, \mathbf{1}, \mathbf{3})$$

$S(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})$ and $U_\mu(\mathbf{3}, \mathbf{1}, \mathbf{1})$ give large $pp \to \tau^+\tau^-$, excluded by Z' searches

$S(\mathbf{1}, \bar{\mathbf{3}}, \mathbf{1})$ and $U_\mu(\mathbf{1}, \mathbf{3}, \mathbf{1})$ give y_c suppressed $B \to D^{(*)}\tau\bar{\nu}$ contributions
$\Rightarrow$ too large couplings, or too light leptoquarks

- Possibly viable: $S(\mathbf{1}, \mathbf{1}, \bar{\mathbf{3}})$ and $U_\mu(\mathbf{1}, \mathbf{1}, \mathbf{3})$ $\Rightarrow$ consider in more detail

Both can be electroweak singlets or triplets

Constraints from $b \to s\nu\bar{\nu}$

- With three Yukawa spurion insertions, one can write:

$$\delta\mathcal{L}' = \lambda' S Y_d^\dagger Y_u Y_u^\dagger \, \bar{q}_L^c i\tau_2 \ell_L$$

- Generates four-fermion operator:

$$\frac{V_{tb}^* V_{ts}}{2m_{S_3}^2} \, y_t^2 y_b^2 \, \lambda'\lambda \, (\bar{b}_L \gamma^\mu s_L \, \bar{\nu}_L \gamma_\mu \nu_L)$$

- Current limits on $B \to K\nu\bar{\nu}$ imply: $\lambda'/\lambda \lesssim 0.1$ — some suppression of λ' required

- Electroweak singlet vector LQ is the only one of the four models w/o this constraint

  (E.g., vector triplet has $\lambda' \, \bar{q}_L Y_u Y_u^\dagger Y_d \, \boldsymbol{\tau} \gamma_\mu \ell_L \boldsymbol{U}^\mu$ term)

- If central values & patterns change, more "mainstream" MFV models may fit