The $B \to D^{(*)}\tau\bar{\nu}$ anomalies: facts and/or fictions

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Aspen Winter Conference, March 19–25, 2017

F. Bernlochner, ZL, D. Robinson, M Papucci, 1703.05330

M. Freytsis, ZL, J. Ruderman, PRD 92 (2015) 054018 [1506.08896]

F. Bernlochner, ZL, PRD 95 (2017) 014022 [1606.09300]

D. Robinson, ZL, M Papucci, JHEP 1701 (2017) 083 [1610.02045]

$+$ works in progress ...

Thanks to Csaba, Erez, Jessie, Tomer, Yuri for the invitation

CA snow conditions ten days ago — “under the lamp post”...

Apologies to Jesse, Ben, Wei...

The scale of new physics?

- SM cannot be the full story — theoretical prejudices of the 1990s didn't pan out
- Are measures of fine tuning misleading, and NP is order of magnitude heavier?
- New physics at LHC — MFV probably useful approximation to its flavor structure

  $\Updownarrow$

  New physics at $10^{1-2}\,\text{TeV}$ — less strong flavor suppression, MFV less motivated
- Discovering deviations from the SM flavor sector is possible in either case

  (deviation from SM $\rightarrow$ upper bound on scale)

- Future: $\frac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \frac{\text{(LHCb lifetime)}}{\text{(LHCb now)}} \sim \frac{\text{(ATLAS \& CMS 3/ab)}}{\text{(ATLAS \& CMS now)}} \sim 50-100$
- Most conservatively: increases in mass scales probed $(\sqrt[4]{50} \sim 2.5)$

  New questions for $100\times$ more data? New theory ideas? Data always motivate theory progress...

Flavor anomalies: (subjective) status

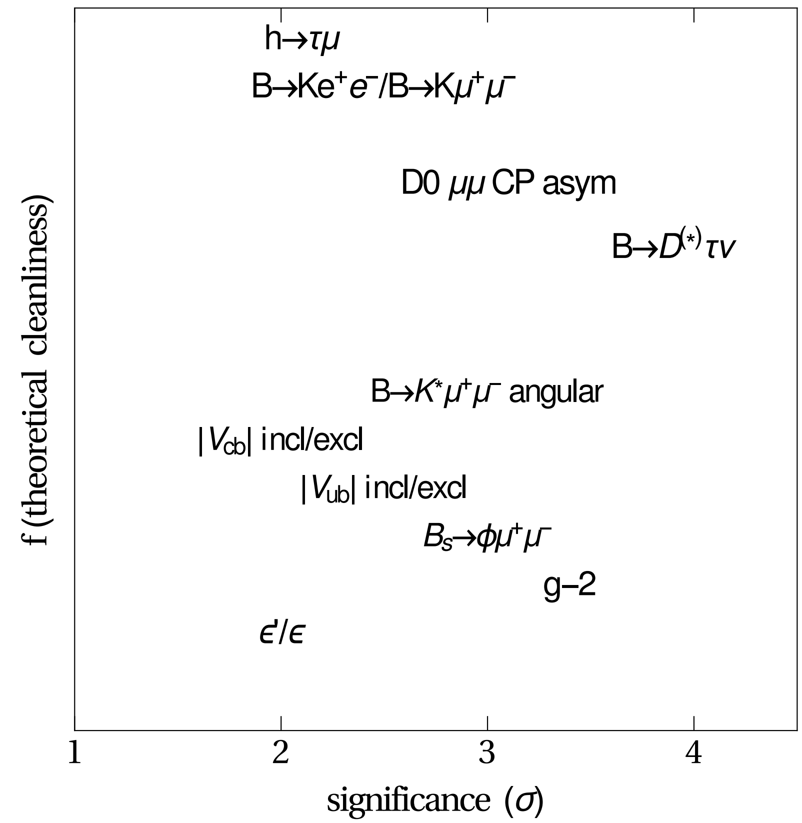
- Several measurements are in intriguing tensions with the SM

  Key roles of Δm_K and ϵ_K remain, to constrain NP vs. flood of LHCb data, exploring Higgs flavor, etc.

- Guaranteed to probe and understand the SM much better (e.g., "new" hadronic states)

  Hope of discovering BSM phenomena

- Each could be a whole a talk...



- Exp.: NA62 taking data, by 2019 measure $K^+ \to \pi^+ \nu\bar\nu$ to $< 10\%$ (at SM level)
  Belle II approaching, time to make genuine predictions is shrinking
  LHCb $300/\text{fb}$ upgrade planning $+$ improving EDM, CLFV, DM, sensitivities

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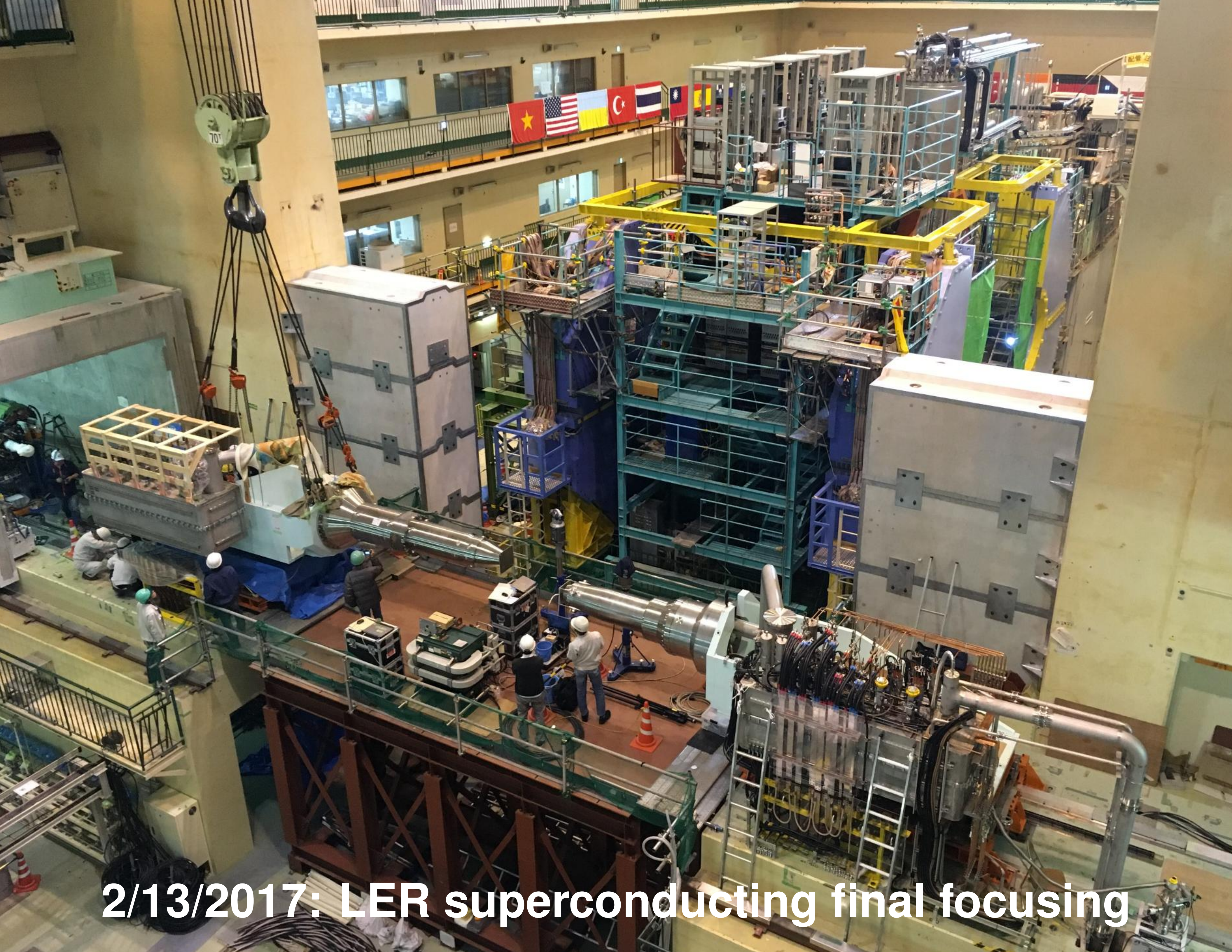


2/13/2017: LER superconducting final focusing

Outline

- $B \to D^{(*)}\tau\bar{\nu}$ is currently the most significant deviation from the SM (at colliders)

1. Use $B \to D^{(*)}l\bar{\nu}$ to refine $B \to D^{(*)}\tau\bar{\nu}$, lattice independent, improvable

   [F. Bernlochner, ZL, Papucci, Robinson, 1703.05330]

   Refine $|V_{cb}|$ determination, test HQET, test lattice, test measurements... [soon]

2. MFV models, leptoquarks [M. Freytsis, ZL, J. Ruderman, PRD 92 (2015) 054018, arXiv:1506.08896]

   Suppress e & μ instead of enhancing τ ? [M. Freytsis, ZL, J. Ruderman, to appear]

3. $B \to D^{**}\ell\bar{\nu}$ in the SM and $R(D^{**})$ [F. Bernlochner, ZL, PRD 95 (2017) 014022, arXiv:1606.09300.]

   $B \to D^{**}\ell\bar{\nu}$ for arbitrary new physics [soon]

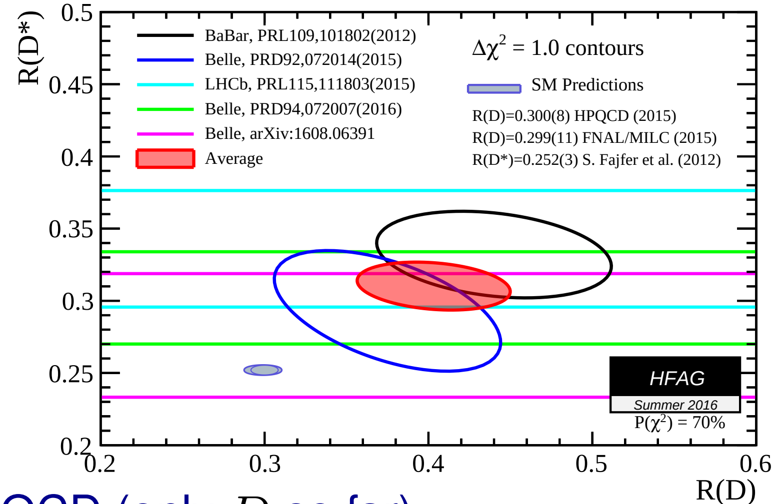
'When you think you can finally forget a topic, it's just about to become important'

The tension with the SM

- BaBar / Belle / LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar\nu)}{\Gamma(B \to X l \bar\nu)}$

  World average: 3.9σ from the SM $\quad l = e, \mu$

	$R(D)$	$R(D^*)$
World average	0.403 ± 0.047	0.310 ± 0.017
my SM expectation	0.299 ± 0.005	0.257 ± 0.005
Belle II	± 0.010	± 0.005



  Reliable SM predictions: heavy quark symmetry + lattice QCD (only D so far)

- Model indep. 2σ tension: $R(D^{(*)})$ vs. $R(X_c) = 0.223 \pm 0.004$ in SM [Freytsis, ZL, Ruderman]

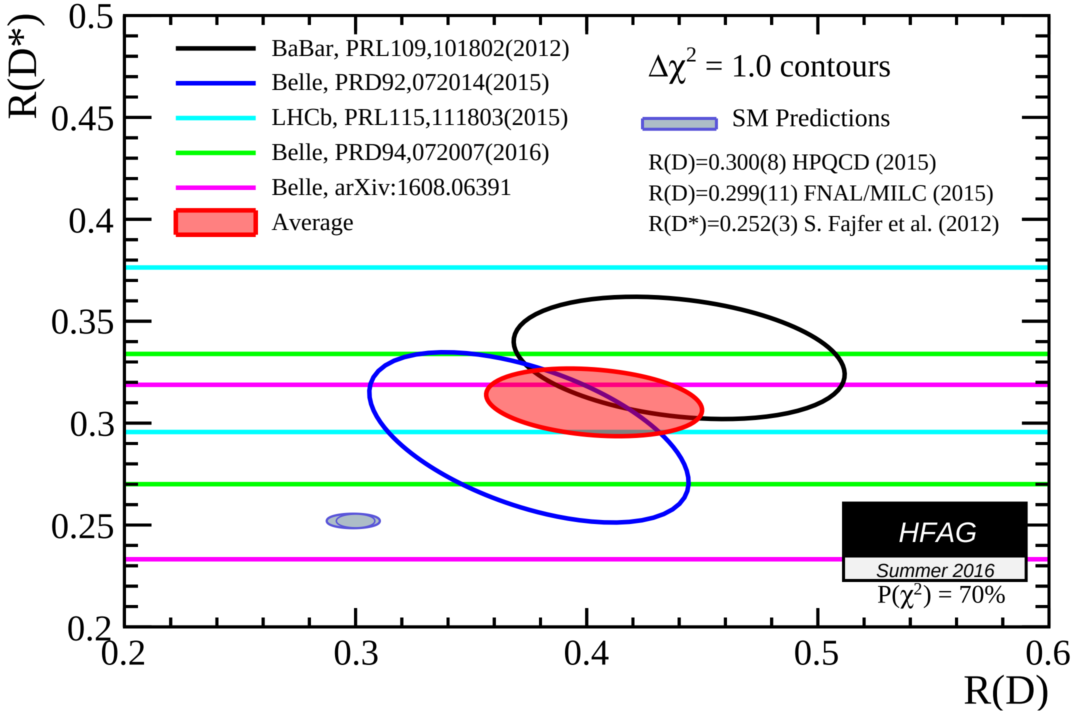
  No $\mathcal{B}(B \to X\tau\bar\nu)$ measurement since LEP, $\mathcal{B}(b \to X\tau^+\nu) = (2.41 \pm 0.23)\%$

  Imply NP at a fairly low scale (leptoquarks, W', etc.), likely visible at the LHC

- Next: LHCb result with hadronic τ decays, measure $R(D)$, maybe Λ_b decay

- Experimental precision will improve a lot + theory uncertainty also improvable

Refining SM predictions



Can it be a theory issue?

Basics of $B \to D^{(*)} \ell \bar\nu$

- Only Lorentz invariance: 6 functions of q^2, only 4 measurable with $e,\ \mu$ final states

$$\langle D|\, \bar c \gamma^\mu b \,|\overline{B}\rangle \;=\; f_+(q^2)(p_B + p_D)^\mu + \Big[f_0(q^2) - f_+(q^2)\Big] \frac{m_B^2 - m_D^2}{q^2}\, q^\mu$$

$$\langle D^*|\, \bar c \gamma^\mu b \,|\overline{B}\rangle \;=\; -ig(q^2)\, \epsilon^{\mu\nu\rho\sigma}\, \varepsilon_\nu^*\, (p_B + p_{D^*})_\rho\, q_\sigma$$

$$\langle D^*|\, \bar c \gamma^\mu \gamma^5 b \,|\overline{B}\rangle \;=\; \varepsilon^{*\mu} f(q^2) + a_+(q^2)\, (\varepsilon^* \cdot p_B)\, (p_B + p_{D^*})^\mu + a_-(q^2)\, (\varepsilon^* \cdot p_B)\, q^\mu$$

Two form factors involving $q^\mu = p_B^\mu - p_{D^{(*)}}^\mu$ do not contribute for $m_l = 0$

- HQET constraints: 6 functions $\Rightarrow 1$ in $m_{c,b} \gg \Lambda_{\rm QCD}$ limit $+\,3$ at $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$

$$\langle D|\, \bar c \gamma^\mu b \,|\overline{B}\rangle \;=\; \sqrt{m_B m_D}\, \Big[h_+(v+v')^\mu + h_-(v-v')^\mu\Big] \qquad w = v_B \cdot v'_{D^{(*)}}$$

$$\langle D^*|\, \bar c \gamma^\mu b \,|\overline{B}\rangle \;=\; i\sqrt{m_B m_{D^*}}\, h_V\, \varepsilon^{\mu\nu\alpha\beta}\, \epsilon_\nu^* v'_\alpha v_\beta$$

$$\langle D^*|\, \bar c \gamma^\mu \gamma^5 b \,|\overline{B}\rangle \;=\; \sqrt{m_B m_{D^*}}\, \Big[h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^* \cdot v)v^\mu - h_{A_3}(\epsilon^* \cdot v)v'^\mu\Big]$$

$m_{c,b} \gg \Lambda_{\rm QCD}$ limit: $h_+ = h_V = h_{A_1} = h_{A_3} = \xi(w)$ and $h_- = h_{A_2} = 0$

- Constrain all 4 functions from $B \to D^{(*)} l \bar\nu \;\Rightarrow\; \mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\ \alpha_s^2)$ uncertainties

Measured spectra for e & μ final states

- 4 functions: two q^2 spectra in $D^{(*)}$ $+$ two q^2-dependent angular distributions in D^*

All form factors $=$ Isgur-Wise function $+\Lambda_{\rm QCD}/m_{c,b} + \alpha_s$ corrections

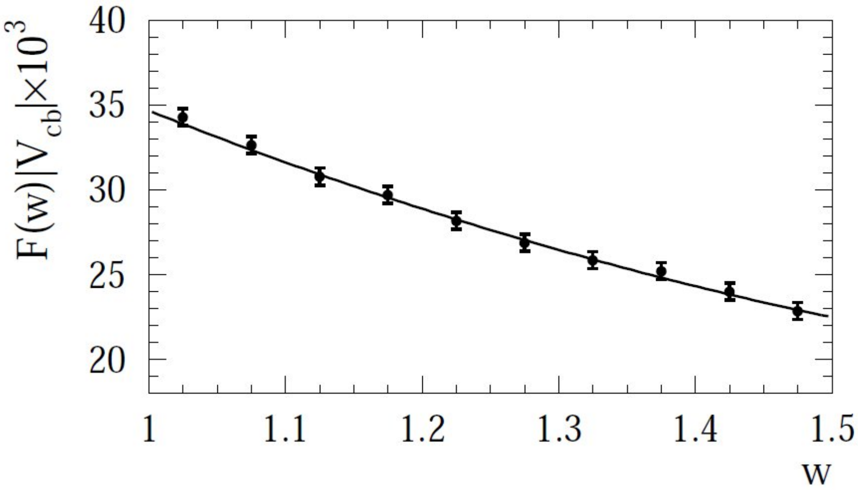
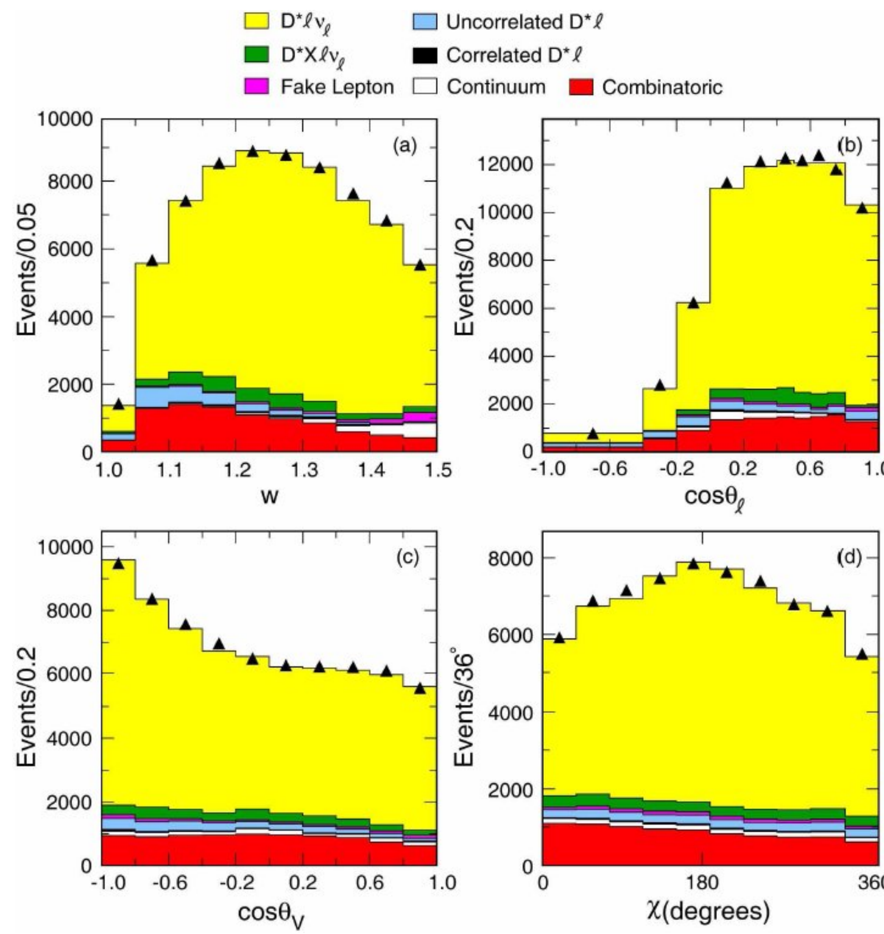


FIG. 6: The measured w dependence of $\mathcal{F}(w)|V_{cb}|$ (data points) compared to the theoretical function with the fitted parameters (solid line). The experimental uncertainties are too small to be visible.

[BaBar, 0705.4008]



Consider 6 different fit scenarios

- Only $R(D)$ calculated in lattice QCD — what are conservative uncertainties?

  Calculations of subleading $\Lambda_{\rm QCD}/m_{c,b}$ Isgur-Wise functions are model dependent

- Except LQCD, past calculations of $R(D^{(*)})$ do not include uncertainties properly

  Both theory and exp papers: $R_{1,2}(w) = \underbrace{R_{1,2}(1)}_{\rm fit} + \underbrace{R'_{1,2}(1)}_{\rm fixed}(w-1) + \underbrace{R''_{1,2}(1)}_{\rm fixed}(w-1)^2/2$

  Sometimes calculations using QCD sum rule predictions for $\Lambda_{\rm QCD}/m_{c,b}$ corrections are called the HQET predictions

- Our fits:

Fit	QCDSR	Lattice QCD $\mathcal{F}(1)$	Lattice QCD $f_{+,0}(1)$	Lattice QCD $f_{+,0}(w>1)$	Belle Data
$\mathrm{L}_{w=1}$	—	+	+	—	+
$\mathrm{L}_{w=1}$+SR	+	+	+	—	+
NoL	—	—	—	—	+
NoL+SR	+	—	—	—	+
th:$\mathrm{L}_{w\geq1}$+SR	+	+	+	+	—
$\mathrm{L}_{w\geq1}$+SR	+	+	+	+	+

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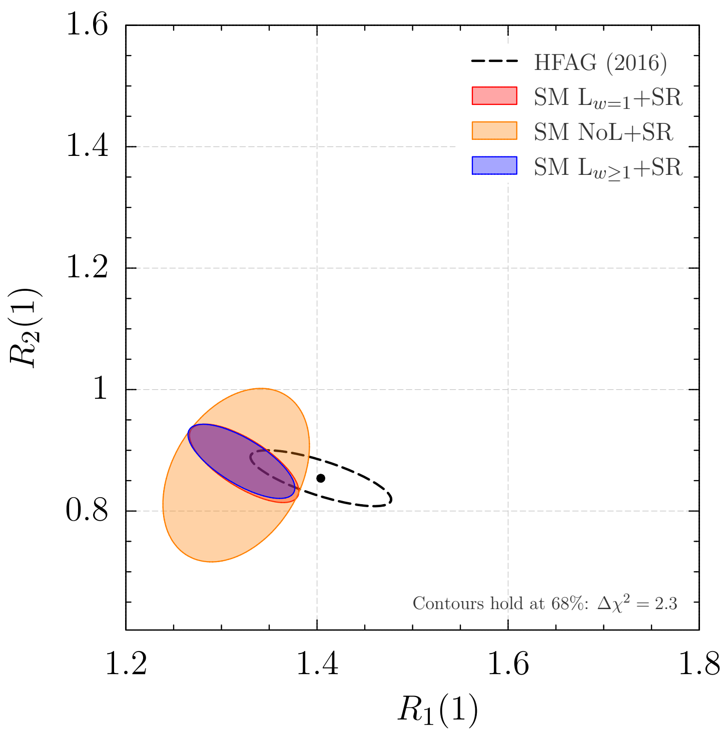
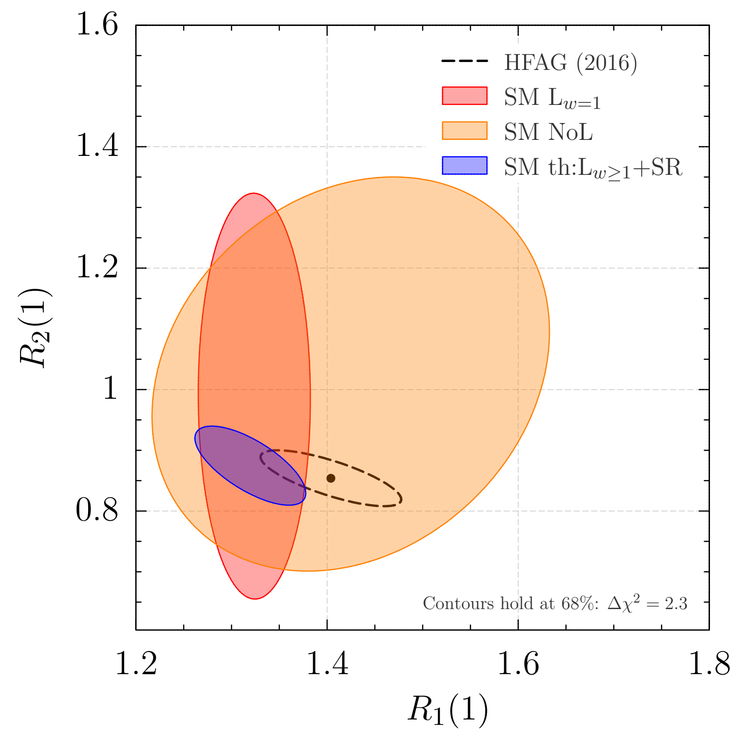
Experimental inputs and self-consistency

- Experimental inputs: $B \to D l \bar{\nu}:\ \mathrm{d}\Gamma/\mathrm{d}w$ (Only Belle published fully corrected distributions)

  $B \to D^* l \bar{\nu}:\ \mathrm{d}\Gamma/\mathrm{d}w,\ R_1(w),\ R_2(w)$



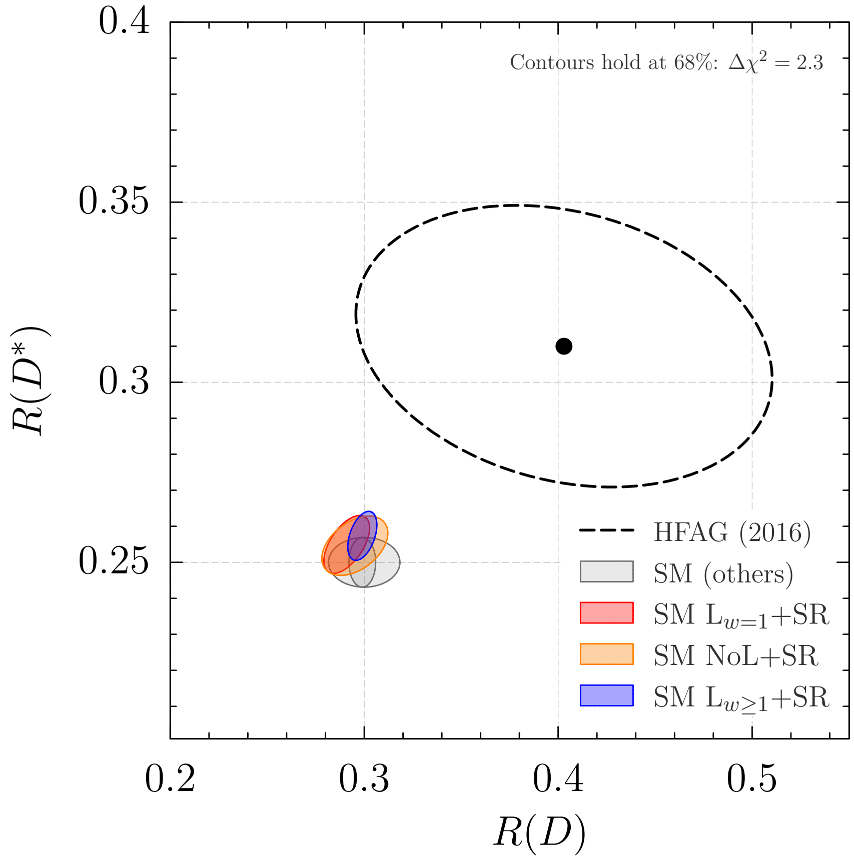


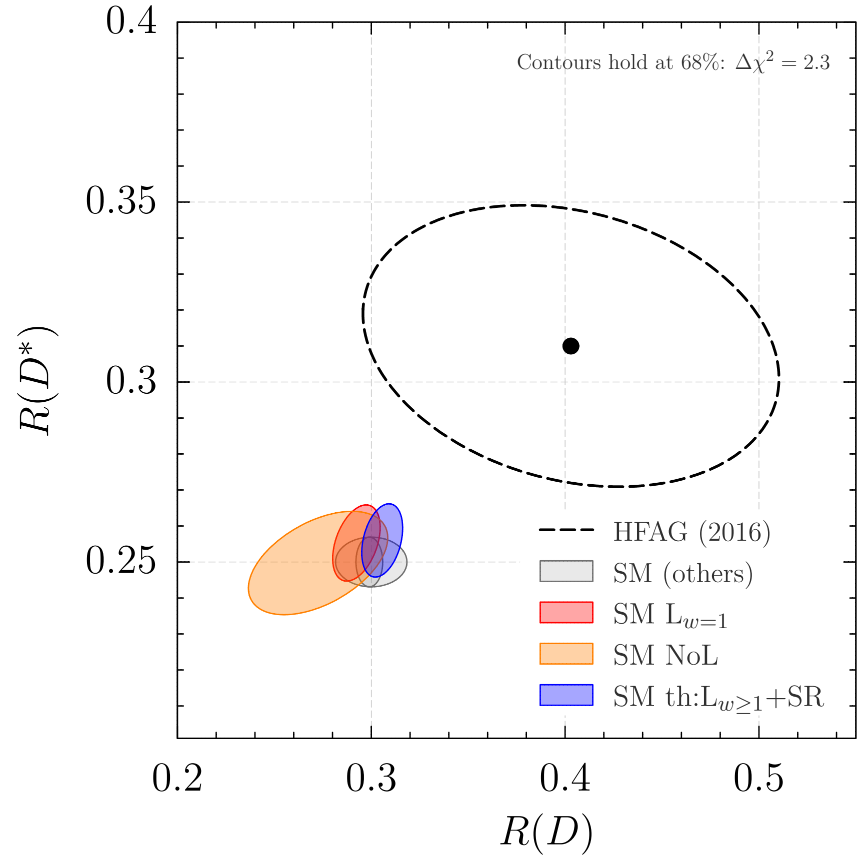
Model-dependent inputs in SM predictions for $R_{1,2}$ in all exp. fits & theory papers

- May affect $|V_{cb}|$ from $B \to D^{(*)} l \bar{\nu}$ — long standing tensions

Our SM predictions for $R(D)$ and $R(D^*)$

- Significance of the tension is stable across our 6 fit scenarios:





E.g., we can use no data at all $+$ LQCD $B \to D^{(*)} l\bar{\nu}$ $+$ HQET form factor ratios

Summary of SM predictions

- Modest variations: heavy quark symmetry & phase space leave little wiggle room

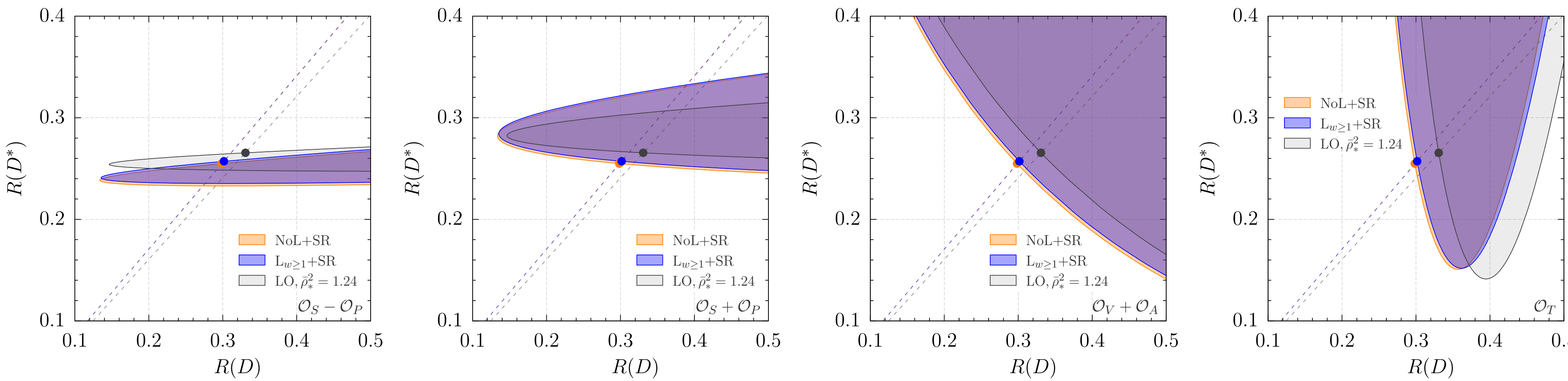
Scenario	$R(D)$	$R(D^*)$	Correlation
$\mathrm{L}_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$\mathrm{L}_{w=1}$+SR	0.291 ± 0.005	0.255 ± 0.003	57%
NoL	0.273 ± 0.016	0.250 ± 0.006	49%
NoL+SR	0.295 ± 0.007	0.255 ± 0.004	43%
th:$\mathrm{L}_{w\geq 1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
$\mathrm{L}_{w\geq 1}$+SR	0.299 ± 0.003	0.257 ± 0.003	44%
Data [HFAG]	0.403 ± 0.047	0.310 ± 0.017	-23%

Tension between our "$\mathrm{L}_{w\geq 1}$+SR" fit and data is 3.9σ, with p-value $= 11.5 \times 10^{-5}$

(close to HFAG: 3.9σ, with p-value $= 8.3 \times 10^{-5}$)

New physics possibilities with one operator

- Add only one NP operator to the SM at a time: $O_S - O_P$, $O_S + O_P$, $O_V + O_A$, O_T



- Not all $1/m$ corrections in literature, some $\mathcal{O}(1/m)$ form factors had 100% uncert.
- Shifts from gray regions non-negligible — if one seriously wanted to fit a NP model

New physics options

Consider redundant set of operators

- Fits to different fermion orderings convenient to understand allowed mediators

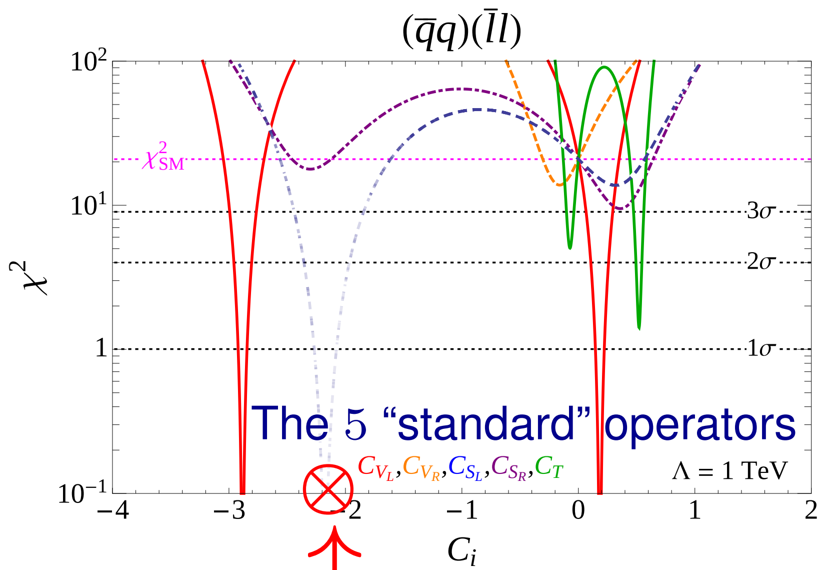
Usually only the first 5 operators considered, related by Fierz

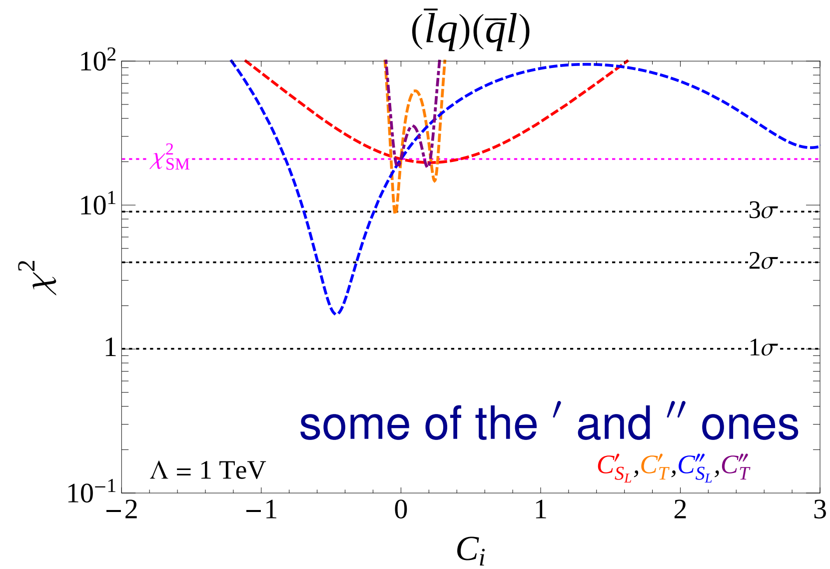
from dim-6 terms, others from dim-8 only $\Downarrow$

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

[Freytsis, ZL, Ruderman, 1506.08896]

Fits to a single operator



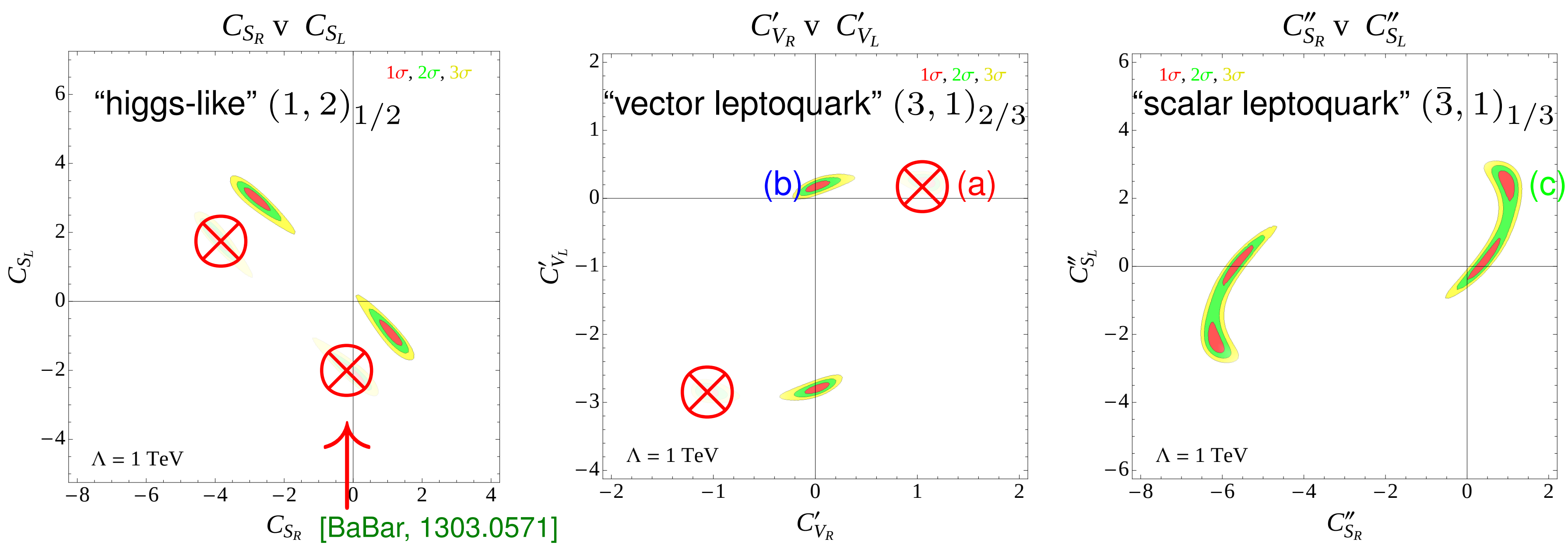


Ruled out by the BaBar q^2 spectrum [1303.0571]

- Large coefficients, $\Lambda = 1\,\text{TeV}$ in plots $\Rightarrow$ fairly light mediators (obvious: 20–30% of a tree-level rate)

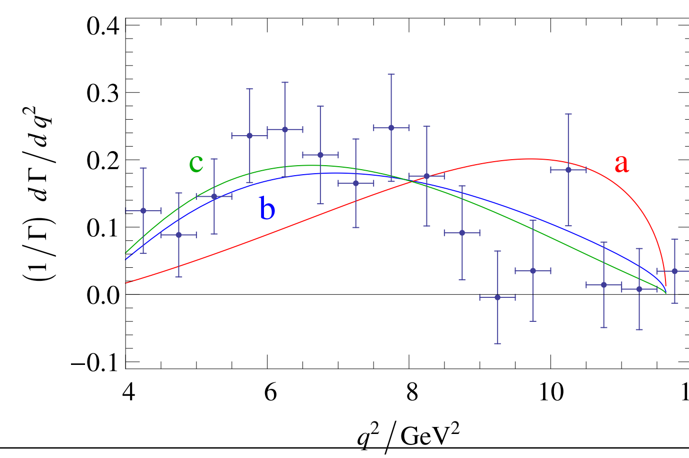
In HQET limit, we confirmed the "classic" paper [Goldberger, hep-ph/9902311]

Fits to two operators



The ⊗ solution are ruled out by the q^2 spectrum

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



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Operator fits → viable MFV 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 $Y_u \sim (\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $Y_d \sim (\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$

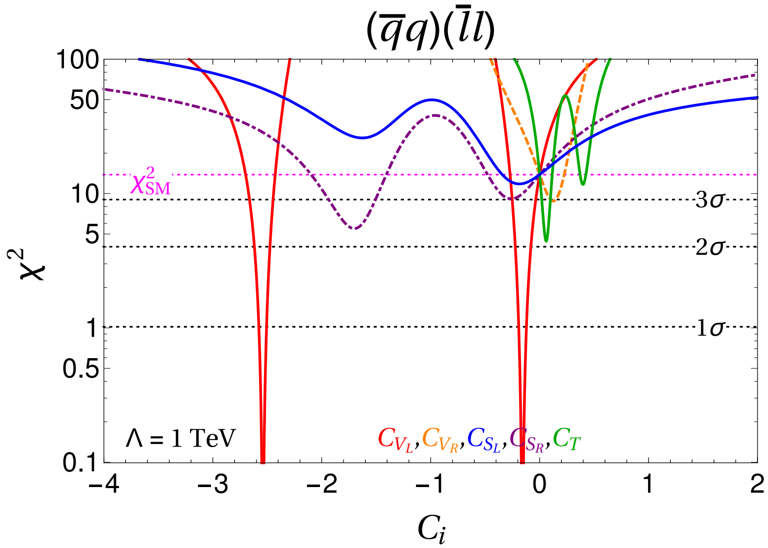
- Which BSM scenarios can be MFV? [Freytsis, ZL, Ruderman, 1506.08896]
  Not scalars or vectors, viable leptoquarks: scalar $S(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$ or vector $U_\mu(\mathbf{1},\mathbf{1},\mathbf{3})$

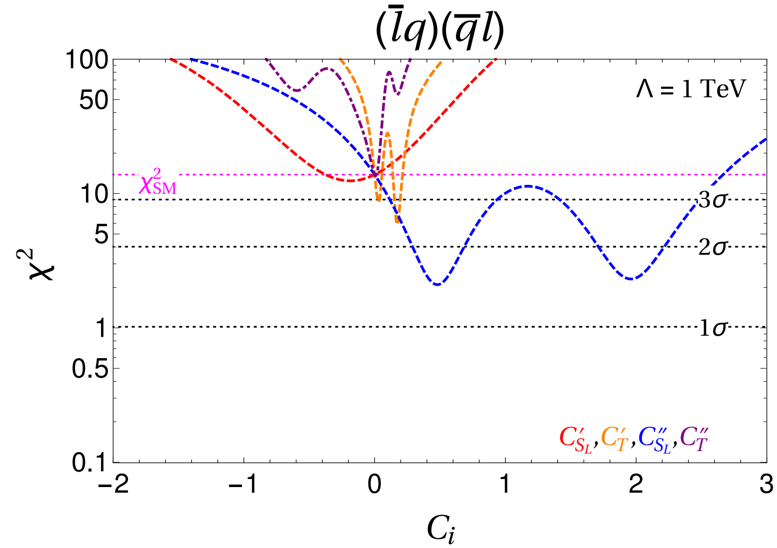
  Bounds: $b \to s\nu\bar{\nu}$, D^0 & K^0 mixing, $Z \to \tau^+\tau^-$, LHC contact int., $pp \to \tau^+\tau^-$, etc.

How odd scenarios may be viable?

- All papers enhance the τ mode compared to the SM

  Can one suppress the e and μ modes instead? [Freytsis, ZL, Ruderman, to appear]





- Unique viable option: modify the SM four-fermion operator

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

- Many relevant constraints, one of the strongest from ϵ_K

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]

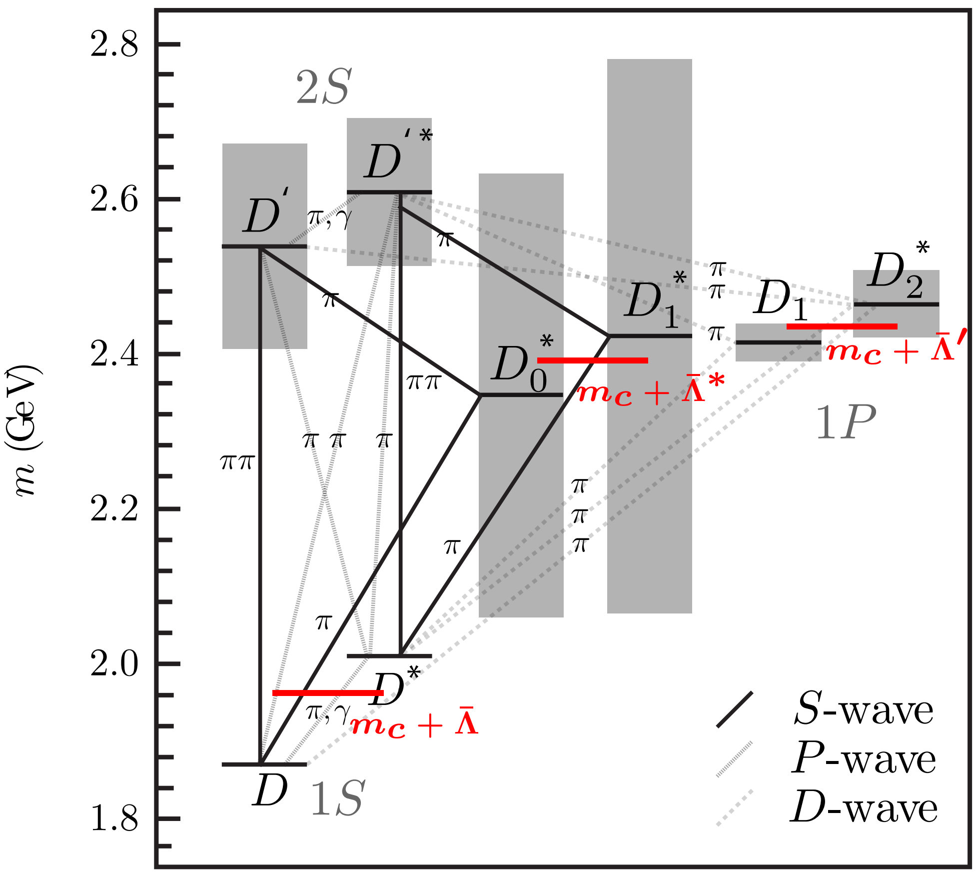
- 10% difference allowed... some wrong statements...

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	$(10.86 \pm 0.16)\%$

- How much better can difference be constrained better?

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

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



Particle	$s_l^{\pi_l}$	J^P	m (MeV)	Γ (MeV)
D_0^*	$\frac{1}{2}^+$	0^+	2330	270
D_1^*	$\frac{1}{2}^+$	1^+	2427	384
D_1	$\frac{3}{2}^+$	1^+	2421	34
D_2^*	$\frac{3}{2}^+$	2^+	2462	48

Parameter	$\bar{\Lambda}$	$\bar{\Lambda}'$	$\bar{\Lambda}^*$
Value [GeV]	0.40	0.80	0.76

Why bother...?

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

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

- Largest syst. uncertainty in $R(D^{(*)})$
- May matter for tensions between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ determinations
- Complementary sensitivity to NP
- Complementary experimentally
- Decay rates not too 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 $1 \le w \lesssim 1.2$

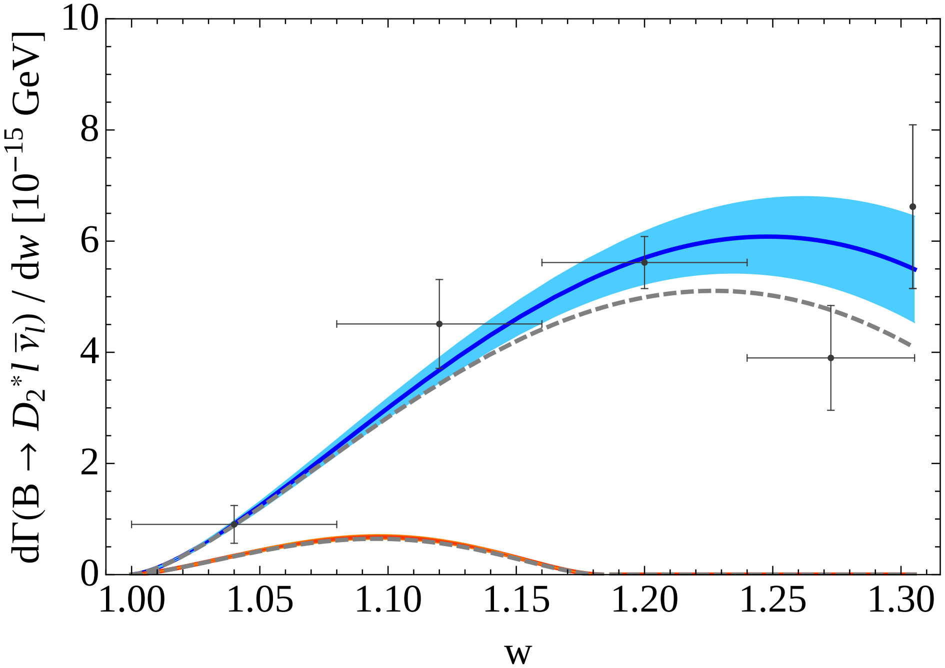
  Meson masses: $$m_{H_\pm} = m_Q + \bar\Lambda^H - \frac{\lambda_1^H}{2m_Q} \pm \frac{n_\mp\, \lambda_2^H}{2m_Q} + \ldots \qquad n_\pm = 2J_\pm + 1$$

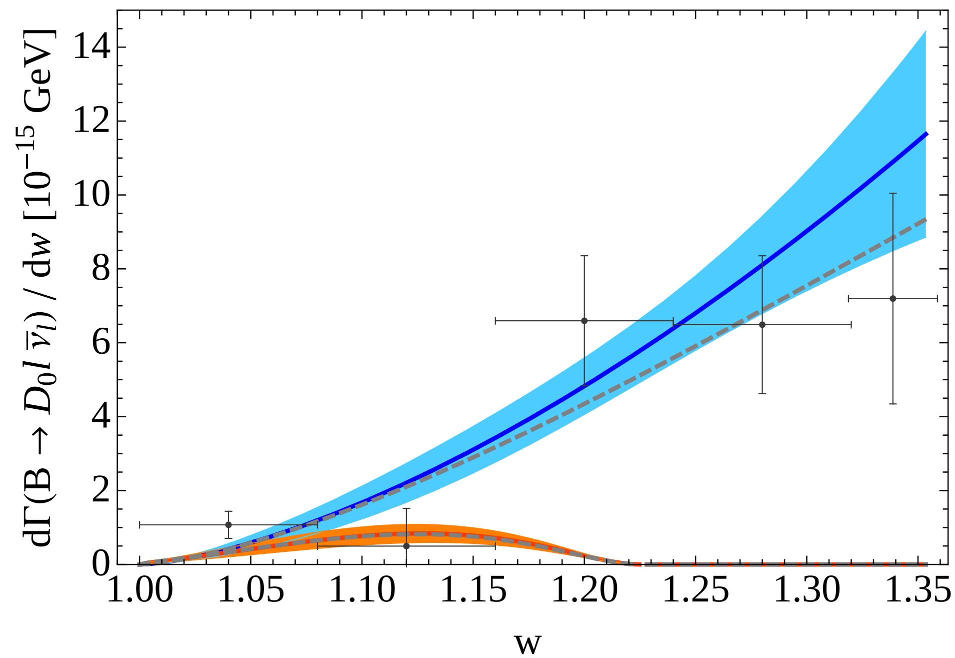
  For example:
  $$\frac{\langle D_1(v',\epsilon)|V^\mu|B(v)\rangle}{\sqrt{m_{D_1}\, m_B}} = f_{V_1} \epsilon^{*\mu} + (f_{V_2} v^\mu + f_{V_3} v'^\mu)(\epsilon^* \cdot v)$$
  $$\sqrt{6}\, f_{V_1}(w) = (1-w^2)\,\tau(w) - 4\,\frac{\bar\Lambda' - \bar\Lambda}{m_c}\,\tau(w) + \mathcal{O}\bigg(\frac{w-1}{m_{c,b}}\bigg)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

- 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...

Predictions for spectra





Rates for e, μ vs. τ

[Data from Belle, 0711.3252]

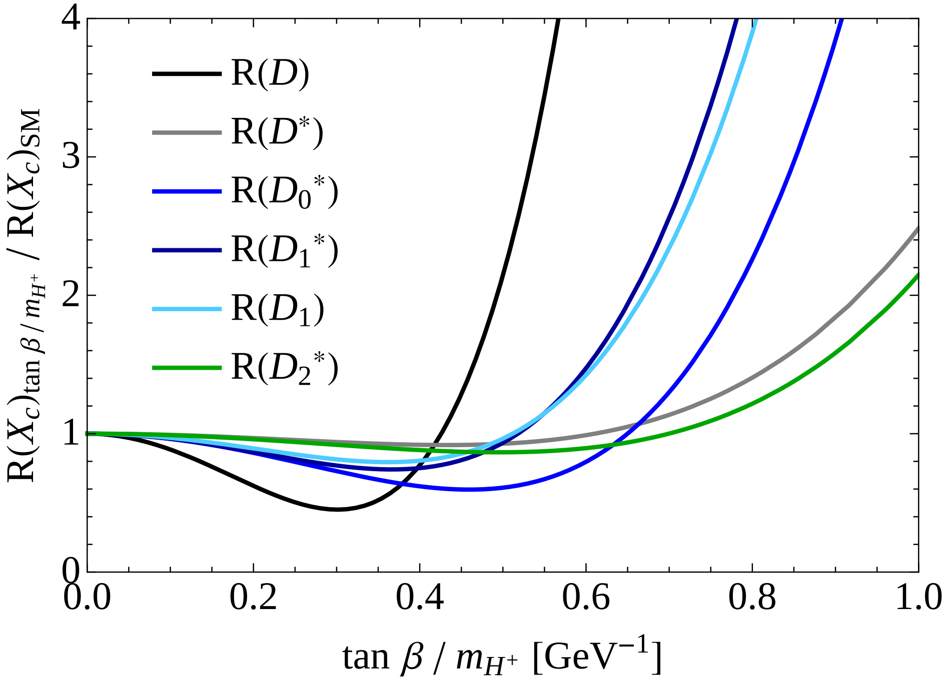
- Study all uncertainties, including effects neglected in LLSW
- As for $B \to D^{(*)}\ell\bar{\nu}$, heavy quark symmetry relates the extra form factor in the τ mode to those with e, μ — finalizing the uncertainties

Complementary sensitivities to NP

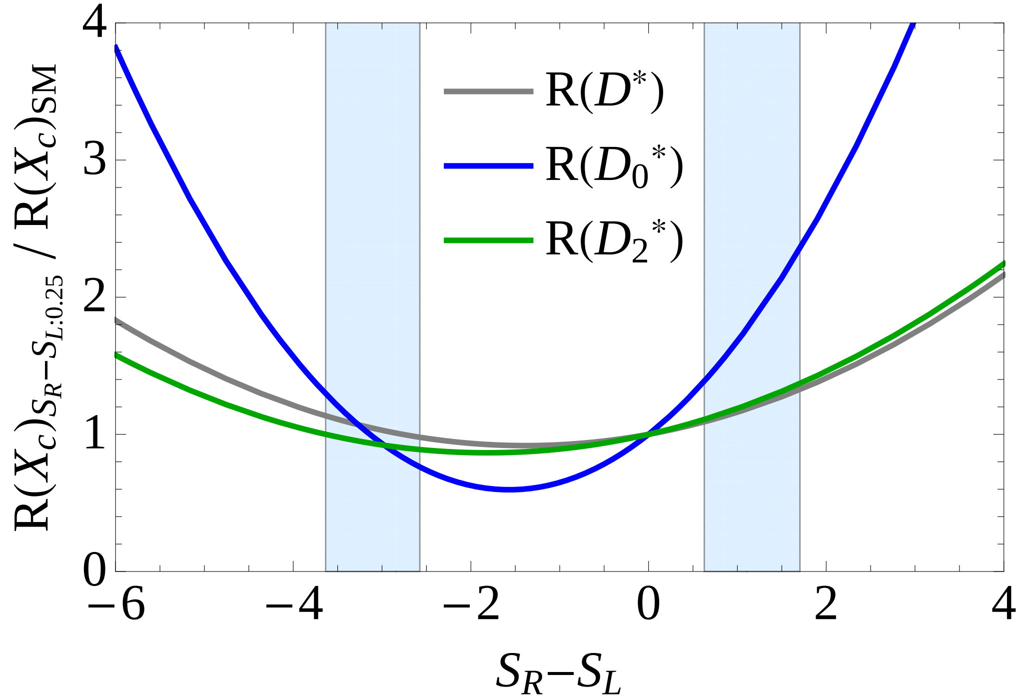
- Complementary sensitivities

[Bernlochner & ZL, 1606.09300]

Type II 2HDM



For fixed $S_R + S_L = 0.25$, favored by BaBar



Different patterns in two blue bands

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

Final comments

Conclusions

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

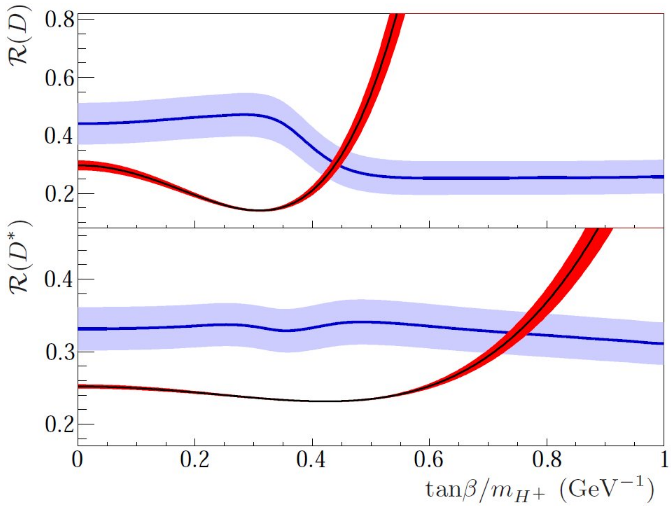
  (Fairly wild scenarios still viable)
- Measurements can improve in the next decade by nearly an order of magnitude

  (Even if central values change, plenty of room for significant deviations from SM)
- More theory progress to come, will impact measurements and sensitivity to BSM

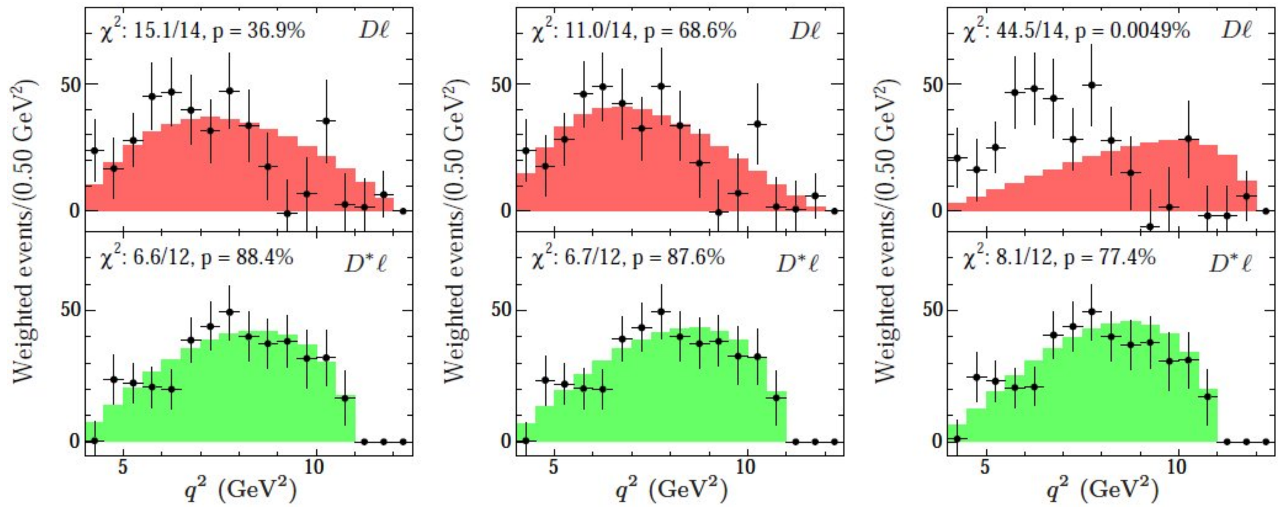
Bonus slides

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

ASPEN CENTER FOR PHYSICS

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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

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 $W'\bar{Q}^3_L Q^3_L$, but not $W'\bar{Q}^i_L Q^i_L$, 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:

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

$S(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})$ 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

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 $b\nu$, $m_{S_3} \gtrsim 560\,\mathrm{GeV}$

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

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

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:

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

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