New predictions for $R(D^{(*)})$

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Mini-workshop on $D^{(*)}\tau\bar{\nu}$ and related topics
Nagoya University, March 27–28, 2017

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

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

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

$+$ works in progress ...

Flavor anomalies: (subjective) status

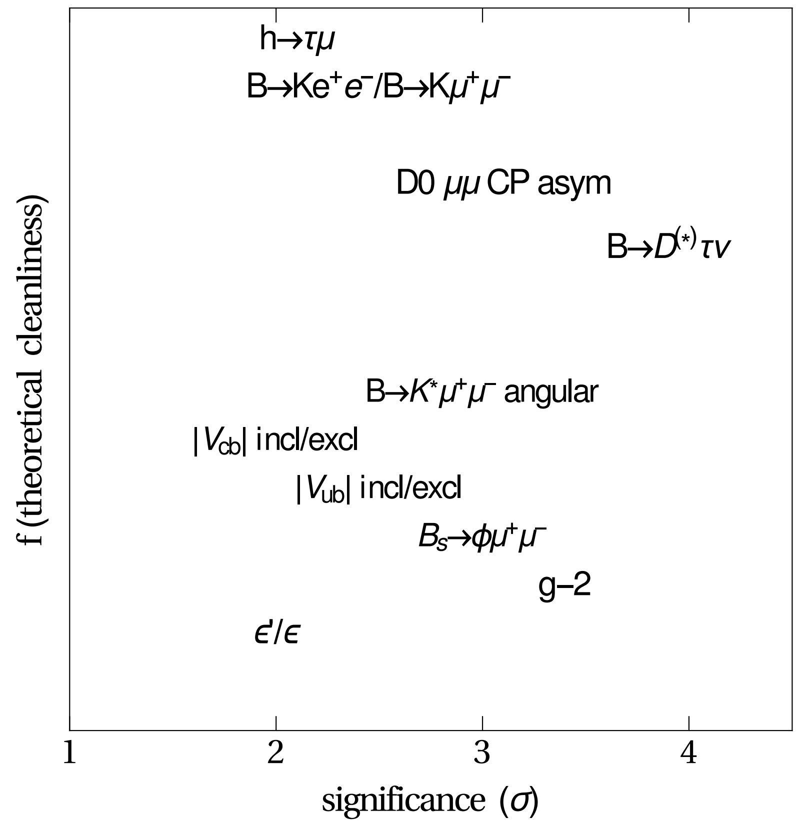
- Several measurements are in intriguing tensions with the SM

  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)

  We'll at least understand inclusive vs. exclusive better...

  Hope of discovering BSM phenomena



- 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 $300/\mathrm{fb}$ upgrade planning $\quad + $ improving EDM, CLFV, DM, sensitivities

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 $R(D^{(*)})$, lattice independent, improvable
   [F. Bernlochner, ZL, Papucci, Robinson, 1703.05330]

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

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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]

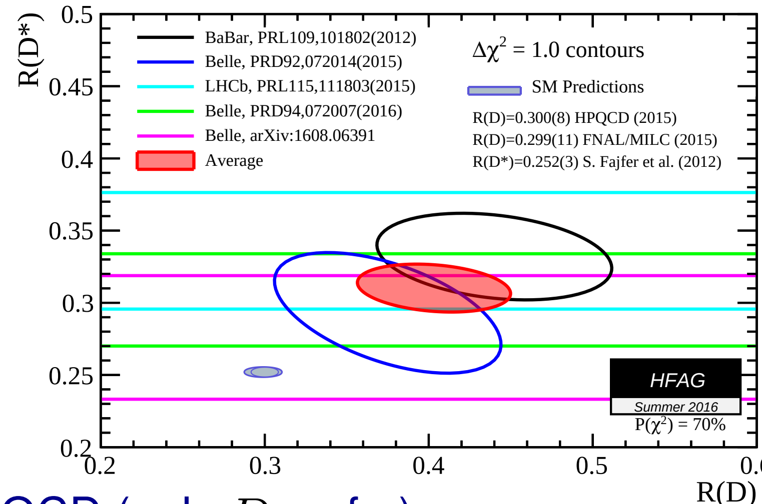
"When you think you can finally forget something, it's about to become important"

The tension with the SM

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

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

	$R(D)$	$R(D^*)$
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]

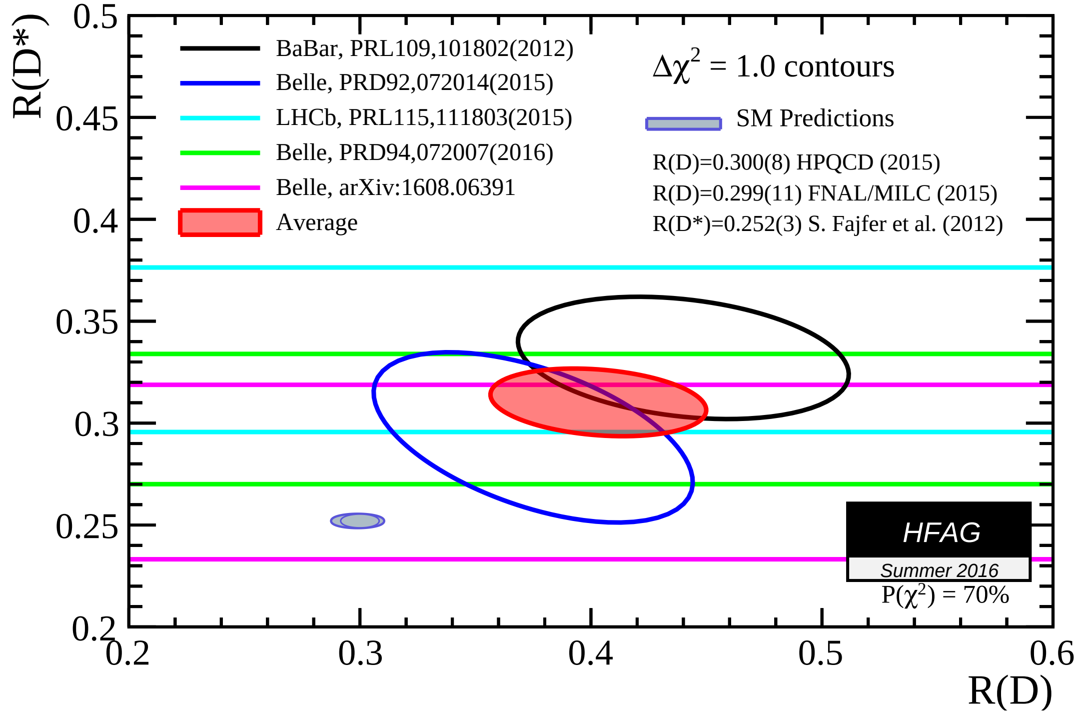
  No $\mathcal{B}(B \to X\tau\bar\nu)$ measurement since LEP, $\mathcal{B}(b \to X\tau^+\nu) = (2.41 \pm 0.23)\%$

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

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

- 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

$$\begin{aligned}
\langle D|\, \bar c\gamma^\mu b\,|\overline{B}\rangle &= f_+(q^2)(p_B+p_D)^\mu + \Big[f_0(q^2) - f_+(q^2)\Big]\frac{m_B^2-m_D^2}{q^2}\,q^\mu \\
\langle D^*|\, \bar c\gamma^\mu b\,|\overline{B}\rangle &= -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon^*_\nu\,(p_B+p_{D^*})_\rho\,q_\sigma \\
\langle D^*|\, \bar c\gamma^\mu\gamma^5 b\,|\overline{B}\rangle &= \varepsilon^{*\mu} f(q^2) + a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\,q^\mu
\end{aligned}$$

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 $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$

$$\begin{aligned}
\langle D|\, \bar c\gamma^\mu b\,|\overline{B}\rangle &= \sqrt{m_B m_D}\,\Big[h_+(v+v')^\mu + h_-(v-v')^\mu\Big] \qquad\qquad w = v_B\cdot v'_{D^{(*)}} \\
\langle D^*|\, \bar c\gamma^\mu b\,|\overline{B}\rangle &= i\sqrt{m_B m_{D^*}}\,h_V\,\varepsilon^{\mu\nu\alpha\beta}\,\epsilon^*_\nu v'_\alpha v_\beta \\
\langle D^*|\, \bar c\gamma^\mu\gamma^5 b\,|\overline{B}\rangle &= \sqrt{m_B m_{D^*}}\,\Big[h_{A_1}(w+1)\epsilon^{*\mu} - h_{A_2}(\epsilon^*\cdot v)v^\mu - h_{A_3}(\epsilon^*\cdot v)v'^\mu\Big]
\end{aligned}$$

$m_{c,b} \gg \Lambda_{\rm QCD}$ 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

Form factor expansion details

- Expand form factors to order $\varepsilon_{c,b} = \Lambda_{\rm QCD}/(2m_{c,b})$ and α_s (new results for tensor ff)

$$f_i(w) = \xi(w)\bigg[1 + \varepsilon_c\, f_i^{(c,1)}(w) + \varepsilon_b\, f_i^{(b,1)}(w) + \alpha_s\, f_i^{(\alpha_s)}\Big(\frac{m_c}{m_b}, w\Big) + \mathcal{O}(\varepsilon_{c,b}^2\,, \alpha_s^2)\bigg]$$

The $\alpha_s\,\varepsilon_{c,b}$ terms are known, should be included if NP established

Expect that fit readjusts subleading Isgur-Wise functions $\Rightarrow$ modest impacts

Known for SM terms since the early 90s, but not written down for others before

Absorbed $\xi(w) \to \xi(w) + 2(\varepsilon_c + \varepsilon_b)\chi_1(w)$, so only $\chi_{2,3}$ and $\eta = \xi_3/\xi$ remain

- Calculated in QCD sum rules — may parametrize them: [Ligeti, Neubert, Nir, '92–'93]

Lagrangian: $\hat\chi_2^{\rm ren}(1) = -0.06 \pm 0.02$ $\quad\hat\chi_2'^{\,\rm ren}(1) = 0 \pm 0.02$ $\quad\hat\chi_3'^{\,\rm ren}(1) = 0.04 \pm 0.02$

Current: $\eta(1) = 0.62 \pm 0.2\,, \quad \eta'(1) = 0 \pm 0.2$ (Luke: $\hat\chi_3(1) = 0$)

Central values match what CLN used, these uncertainties $>$ in original papers

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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

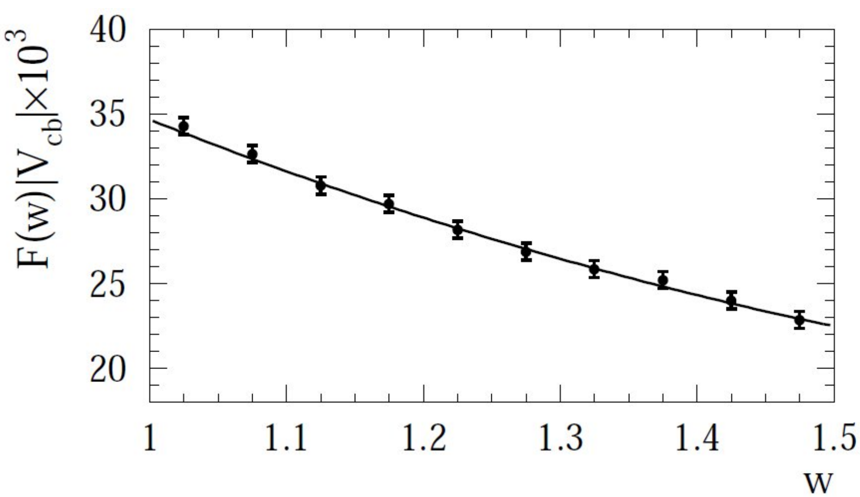
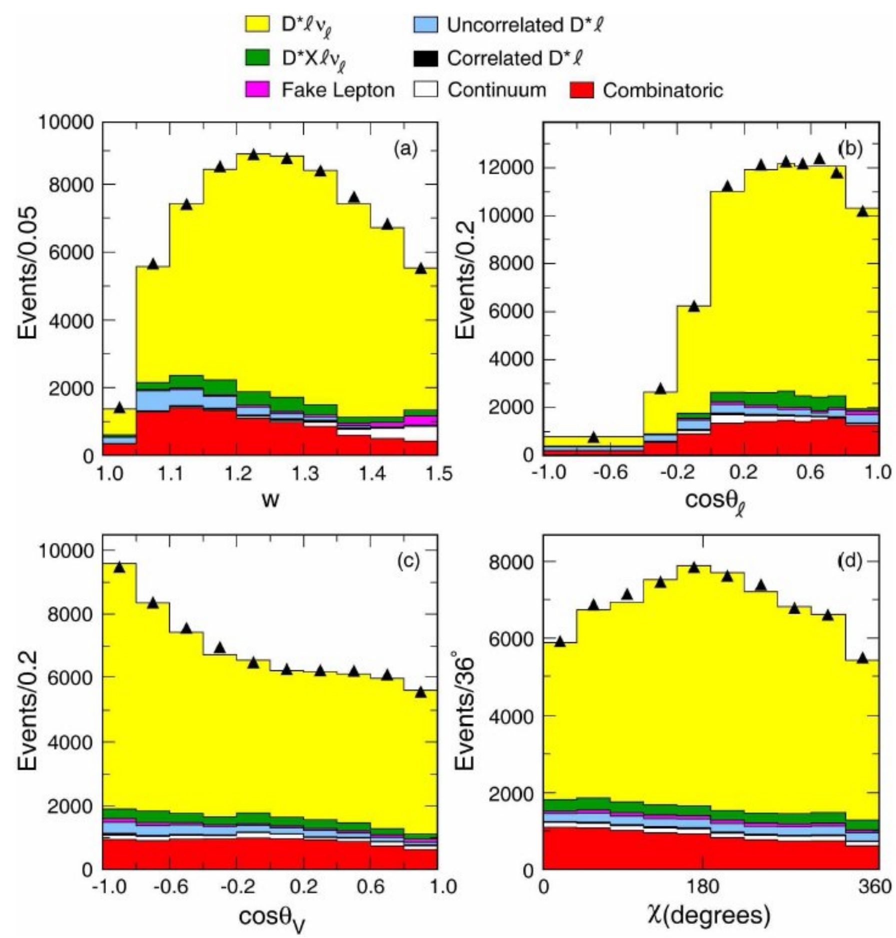


FIG. 6: The measured w dependence of $\mathcal{F}(w)|V_{cb}|$ (data points) compared to the theoretical function with the fitted parameters (solid line). The experimental uncertainties are too small to be visible.



[Plot from BaBar 0705.4008; only Belle unfolded 1510.03657, 1702.01521]

Consider 7 different fit scenarios

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

  Only $R(D)$ calculated in LQCD — all others did not include uncertainties properly

- Theory [CLN] & exp papers: $R_{1,2}(w) = \underbrace{R_{1,2}(1)}_{\rm fit} + \underbrace{R'_{1,2}(1)}_{\rm fixed}(w-1) + \underbrace{R''_{1,2}(1)}_{\rm fixed}(w-1)^2/2$

  In HQET: $R_{1,2}(1) = 1 + \mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}\,,\,\alpha_s)$ $\quad R^{(n)}_{1,2}(1) = 0 + \mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}\,,\,\alpha_s)$

  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			Belle Data
		$\mathcal{F}(1)$	$f_{+,0}(1)$	$f_{+,0}(w>1)$	
L$_{w=1}$	—	+	+	—	+
L$_{w=1}$+SR	+	+	+	—	+
NoL	—	—	—	—	+
NoL+SR	+	—	—	—	+
L$_{w\geq 1}$	—	+	+	+	+
L$_{w\geq 1}$+SR	+	+	+	+	+
th:L$_{w\geq 1}$+SR	+	+	+	+	—

Fit details

- Standard choice to minimize range of expansion param' z_* in unitarity constraints:

$$z_*(w) = \frac{\sqrt{w+1} - \sqrt{2}\,a}{\sqrt{w+1} + \sqrt{2}\,a}\,, \qquad a = \left(\frac{1+r_D}{2\,\sqrt{r_D}}\right)^{1/2}$$

- Parametrize similar to CLN — wanted to start with fit comparable to prior results

$$\frac{\mathcal{G}(w)}{\mathcal{G}(w_0)} \simeq 1 - 8a^2\rho_*^2\, z_* + \left(V_{21}\rho_*^2 - V_{20}\right) z_*^2$$

Translate this to $\xi(w)/\xi(w_0)$ to be able to simultaneously fit $B \to D$ and $B \to D^*$

Uncertainty in z_*^2 term may be sizable — we checked that fit results are stable if constraint between the slope and the curvature is relaxed

Keep uncertainties and correlations in form factor ratios ($\Lambda_{\rm QCD}/m$ Isgur-Wise fn's)

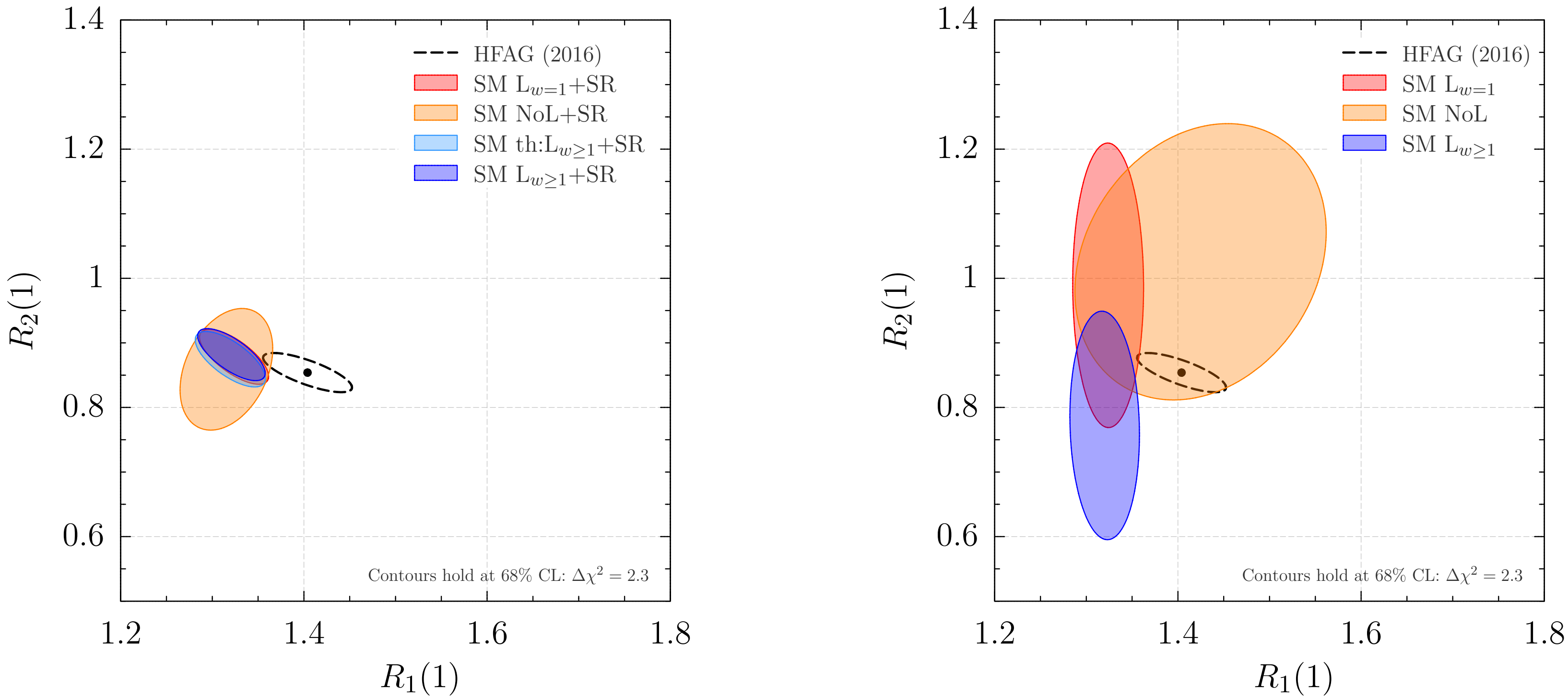
- In progress: study systematically orders/constraints in fit, HQET corrections, etc.

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



- Mild tension for $R_1(1)$ — may affect $|V_{cb}|$ from $B \to D^{(*)} l \bar\nu$, long standing issues

  In $1S$ scheme: $R_1(1) \simeq 1.34 - 0.12\,\eta(1)\,,\qquad R_2(1) \simeq 0.98 - 0.42\,\eta(1) - 0.54\,\hat\chi_2(1)$

Other place where $\Lambda_{\rm QCD}/m_{c,b}$ matters

- At EPS 2001, Ben and I got puzzled by surprising plots...

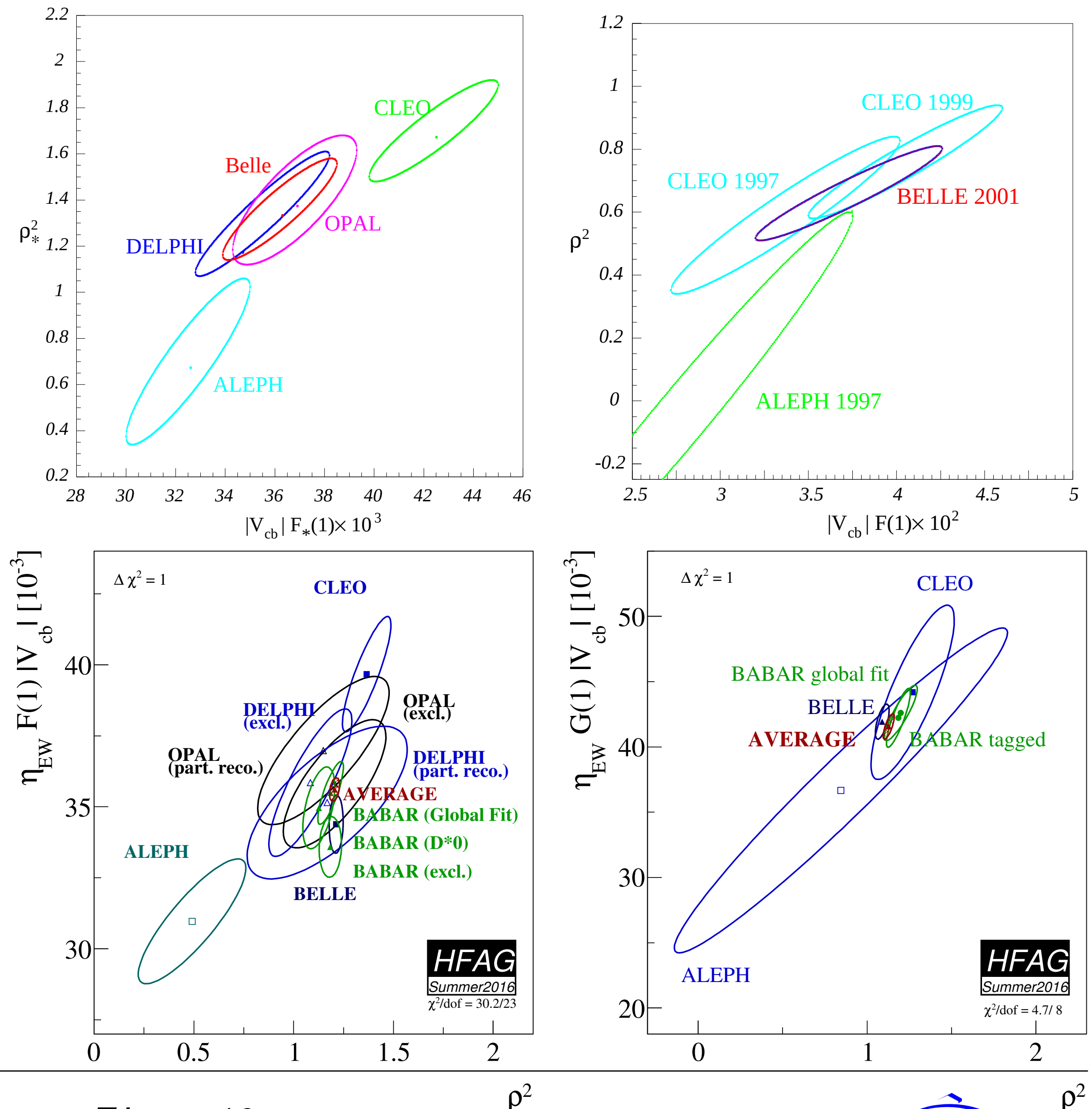
  So we considered corrections up to $\Lambda_{\rm QCD}/m_{c,b}$ and $\alpha_s^2\beta_0$ to the slopes, curvatures, $R_{1,2}$ ...

  [PLB 526 (2002) 345 (2002), hep-ph/0111392]

- Current plots from HFAG 2016:

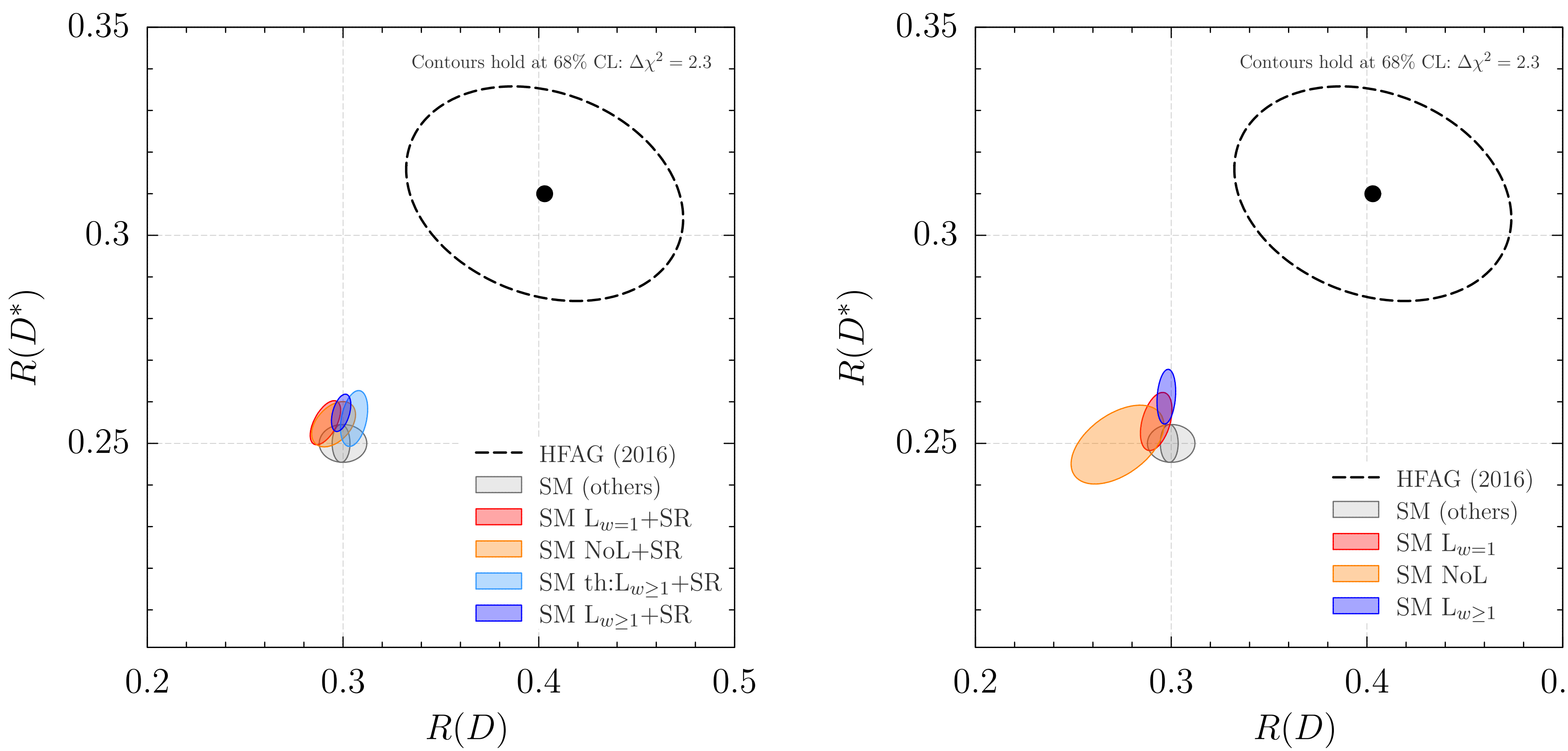
  $\rho^2_{\mathcal{G}} \simeq \rho^2_{A_1}$, as expected

  All this is folded into our fits



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

- Significance of the tension is (surprisingly) stable across our fit scenarios:



- Fit just a quadratic polynomial in z_*: consistent results

Summary of SM predictions

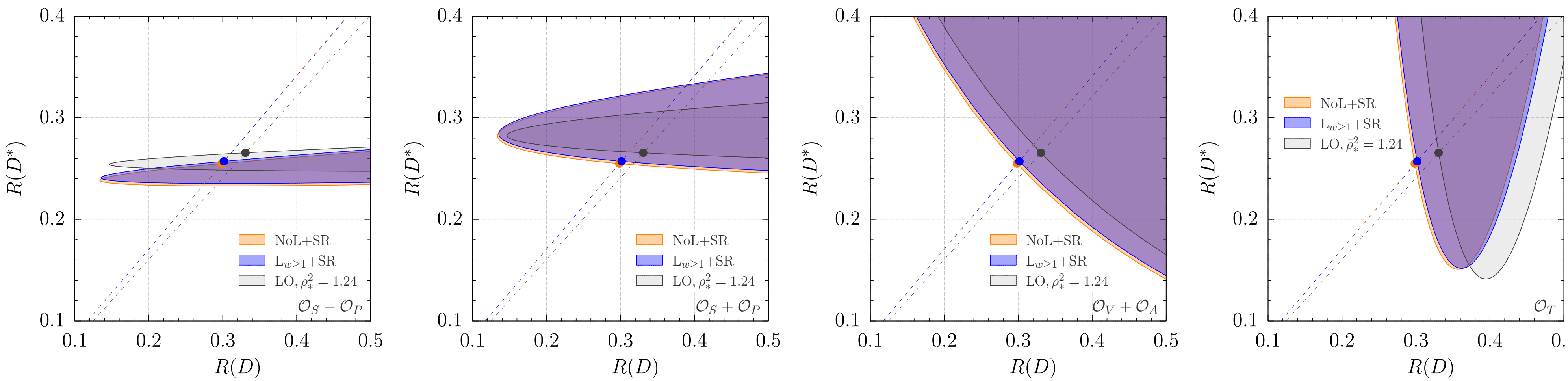
- Small variations: heavy quark symmetry & phase space leave little wiggle room

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%
$\mathrm{L}_{w\geq1}$	0.298 ± 0.003	0.261 ± 0.004	19%
$\mathbf{L}_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	44%
th:$\mathrm{L}_{w\geq1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
Data [HFAG]	0.403 ± 0.047	0.310 ± 0.017	-23%
Lattice [FLAG]	0.300 ± 0.008	—	—
Bigi, Gambino '16	0.299 ± 0.003	—	—
Fajfer et al. '12	—	0.252 ± 0.003	—

- Tension between our "$\mathrm{L}_{w\geq1}$+SR" fit and data is 3.9σ, with p-value $= 11.5 \times 10^{-5}$
(close to HFAG: 3.9σ, with p-value $= 8.3 \times 10^{-5}$)

Impact on new physics effects

- 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

Few comments on new physics

Consider redundant set of operators

- Fits to different fermion orderings convenient to understand allowed mediators

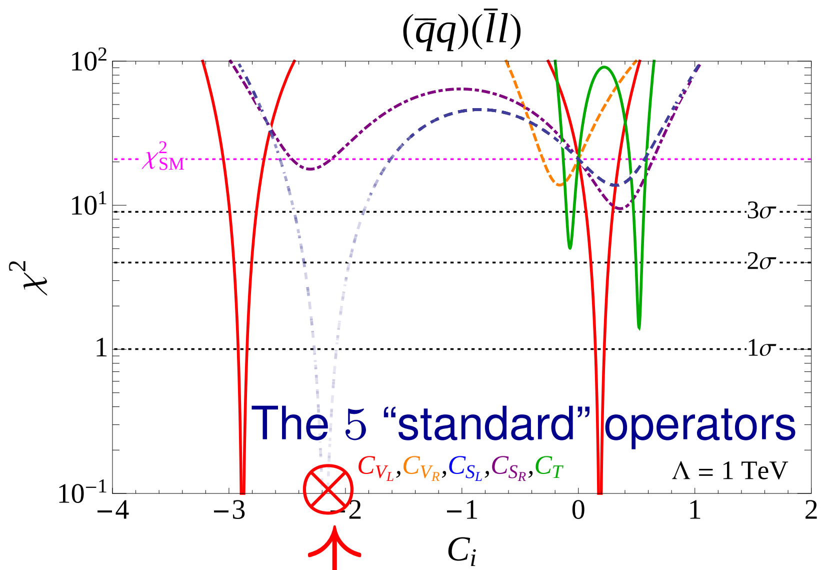
Usually only the first 5 operators considered, related by Fierz

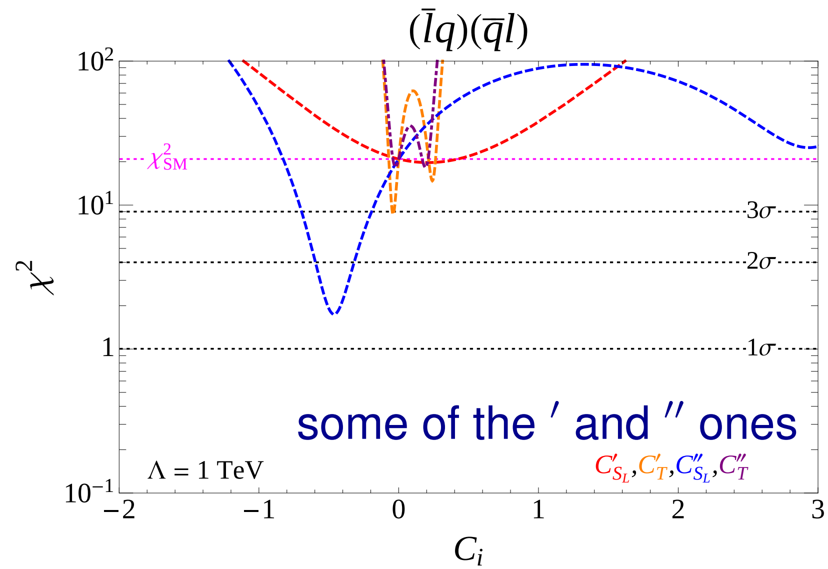
from dim-6 terms, others from dim-8 only $\Downarrow$

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

[Freytsis, ZL, Ruderman, 1506.08896]

Fits to a single operator



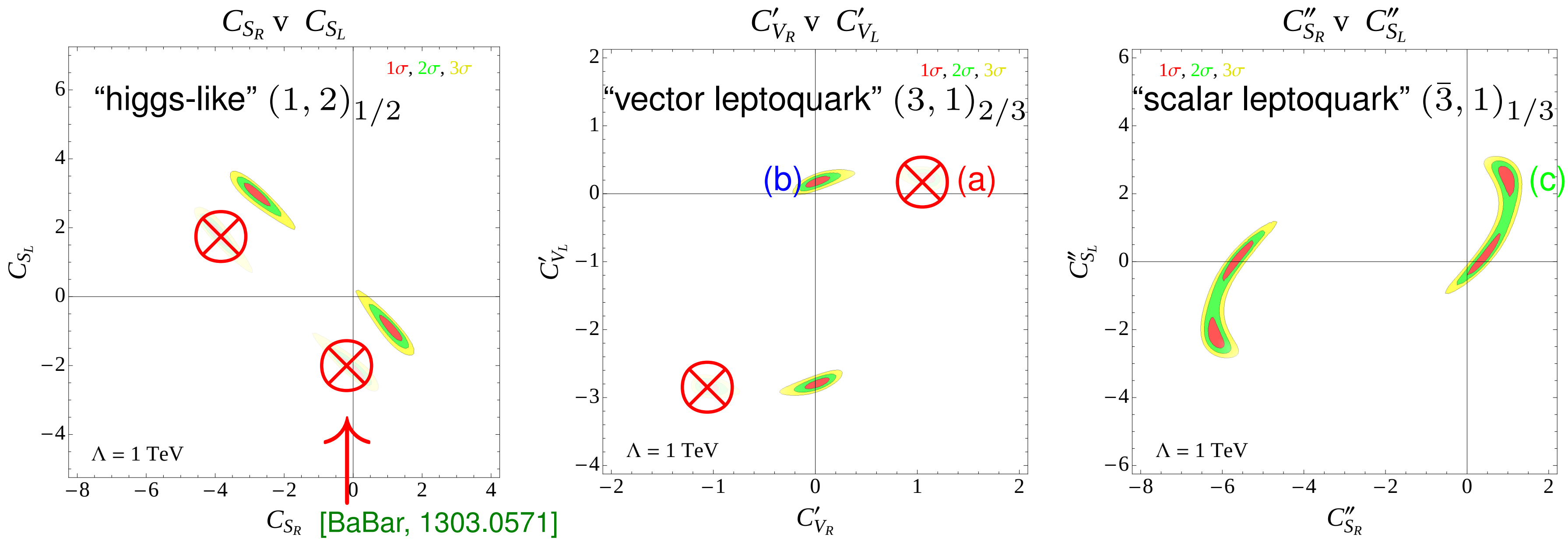


Ruled out by the BaBar q^2 spectrum [1303.0571]

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

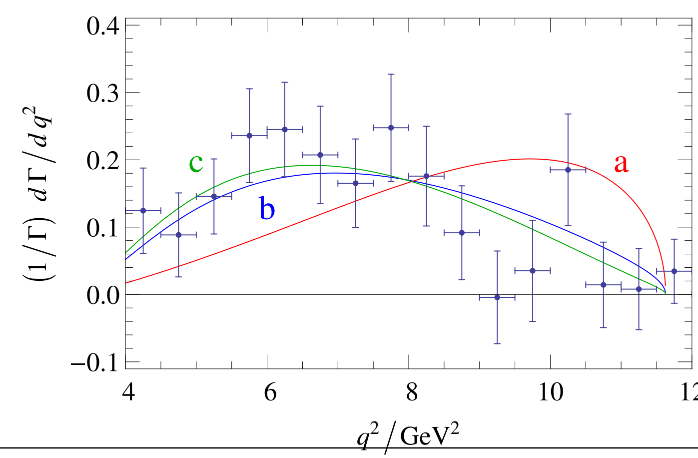
In HQET limit, we confirmed the “classic” paper [Goldberger, hep-ph/9902311]

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?

- Viable mediators: scalar, "Higgs-like" $(1,2)_{1/2}$, vector, "W'-like" $(1,3)_0$
  "scalar LQ" $(\bar{3},1)_{1/3}$ or $(\bar{3},3)_{1/3}$, "vector LQ" $(3,1)_{2/3}$ or $(3,3)_{2/3}$

- Flavor structure of TeV-scale NP cannot be generic — surprising if only $(\bar{b}c)(\bar{\tau}\nu)$

- New physics at LHC — MFV probably useful approximation to its flavor structure
  $\Updownarrow$
  New physics at $10^{1-2}\,\mathrm{TeV}$ — less strong flavor suppression, MFV less motivated

- 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 $Y_u \sim (\mathbf{3},\bar{\mathbf{3}},\mathbf{1})$, $Y_d \sim (\mathbf{3},\mathbf{1},\bar{\mathbf{3}})$

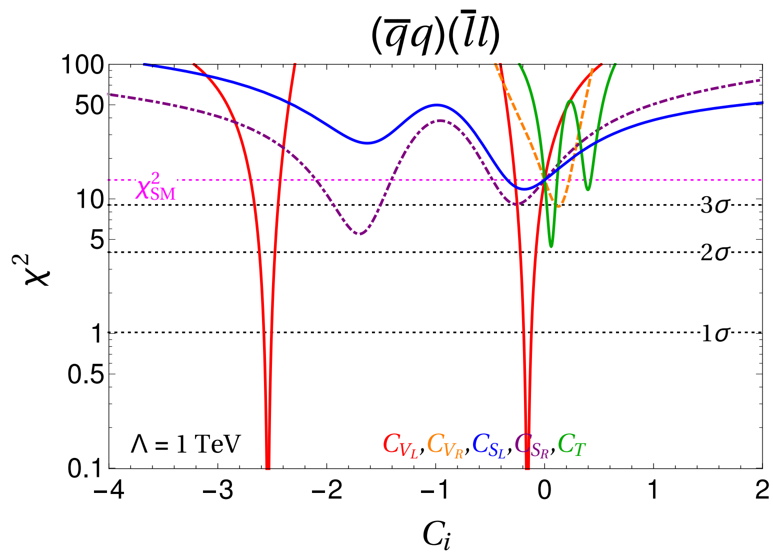
- Which BSM scenarios can be MFV? [Freytsis, ZL, Ruderman, 1506.08896]
  Not scalars or vectors, viable leptoquarks: scalar $S(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$ or vector $U_\mu(\mathbf{1},\mathbf{1},\mathbf{3})$

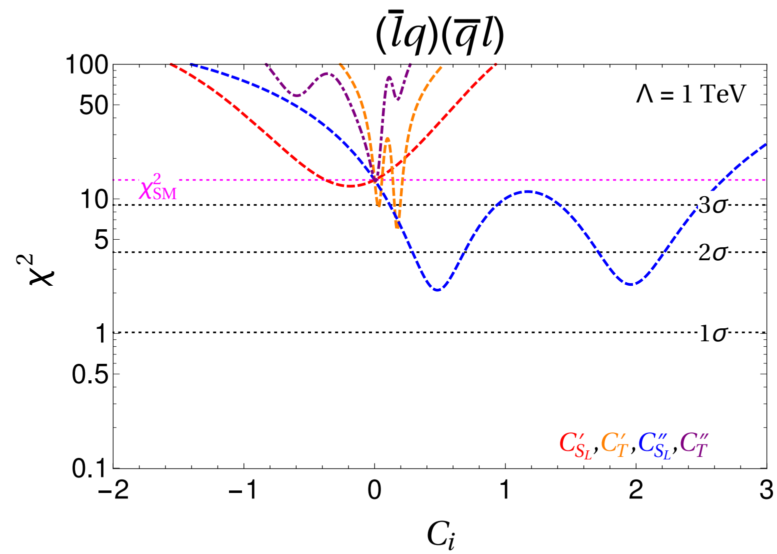
  Bounds: $b \to s\nu\bar{\nu}$, D^0 & K^0 mixing, $Z \to \tau^+\tau^-$, LHC contact int., $pp \to \tau^+\tau^-$, etc.

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

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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

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Final comments

Conclusions

- Amusing if NP shows up in $B \to D^{(*)}\tau\bar{\nu}$, a mode with little SM suppression
- SM predictions can be improved with more data (with continuum methods)
- Lattice: Calculate subleading Isgur-Wise functions and/or non-SM form factors?
- Ongoing: consistent generator for all six $B \to D^{(*,**)}\ell\bar{\nu}$ modes, for any interaction
- More theory progress to come, will impact measurements and sensitivity to BSM
- With Belle II and LHCb upgrade, even if $R(D^{(*)})$ move toward SM, plenty of room to discover NP

- There are good operator fits, and (somewhat) sensible MFV leptoquark models

  (Wild scenarios are also viable!)

Bonus slides