Triangulating $b \to c\tau\bar{\nu}$ at high p_T

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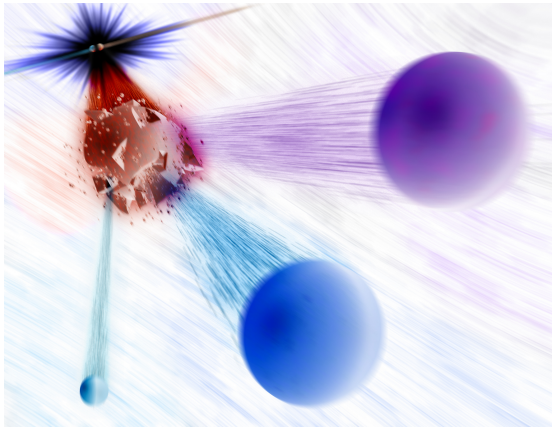
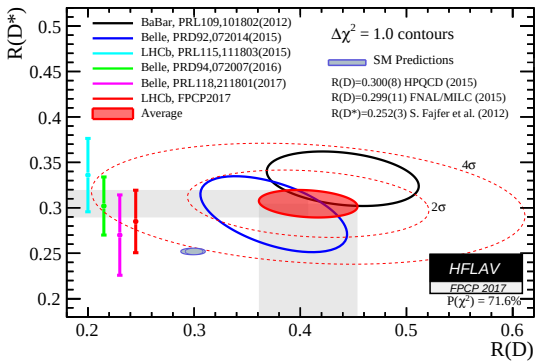


An $R(X)$ primer

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})} \qquad \text{here } \ell = \text{avg. of } \mu, e$$

- first deviations at BaBar, then Belle and LHCb original goal: 2HDM $H^{\pm}$

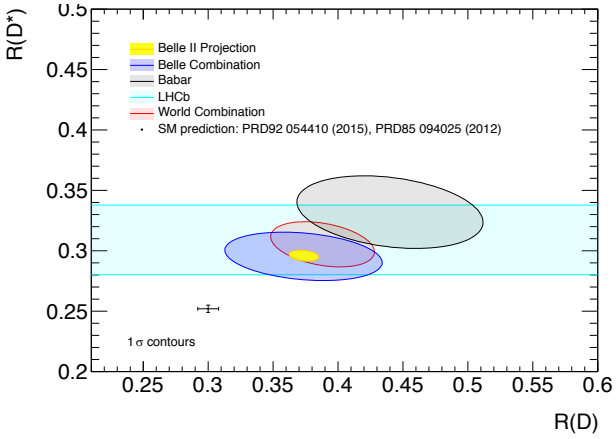
	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Belle ($B_{\text{tag}}^{(\ell)}$)		$0.302 \pm 0.030 \pm 0.011$
Belle ($\tau_{1\text{pr}}$)		$0.270 \pm 0.035 \pm 0.028$
LHCb ($\tau_{3\pi}$)		$0.285 \pm 0.019 \pm 0.029$
Exp. average	$0.407 \pm 0.039 \pm 0.024$	$0.304 \pm 0.013 \pm 0.007$
SM expectation	0.299 ± 0.003	0.257 ± 0.003
Belle II, 50/ab	± 0.010	± 0.005

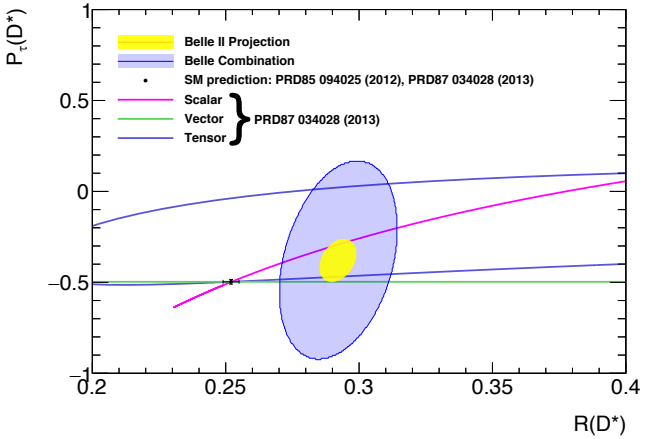


- clean SM observables: heavy quark symmetry
  cancellation of hadronic uncertainties in ratios
  lattice, $R(D)$ only [1607.00299]
- now also $R(J/\psi)_{\text{exp}} = 0.71 \pm 0.17 \pm 0.18$ ($R_{\text{SM}} = 0.25$–0.28) [LHCb, 1711.05623]
- $R(D)$ — 2.3σ, $R(D^*)$ — 3.4σ
  total significance — $\gtrsim 4.1\sigma$ largest deviation from SM right now!

Future of ratios

- continuous improvement on $R(X)$ in coming years
  - LHCb: rich program of initial states
    better $R(J/\psi)$, $R(D)$? $\Lambda_b \to \Lambda_c^{(*)}\tau\bar{\nu}$? $R(D_s)$?
  - Belle II: $O(0.01)$ projections on $R(D^{(*)})$
    more results of Belle dataset: inclusive $B \to X_c\tau\bar{\nu}$? additional $R(D)$ modes?





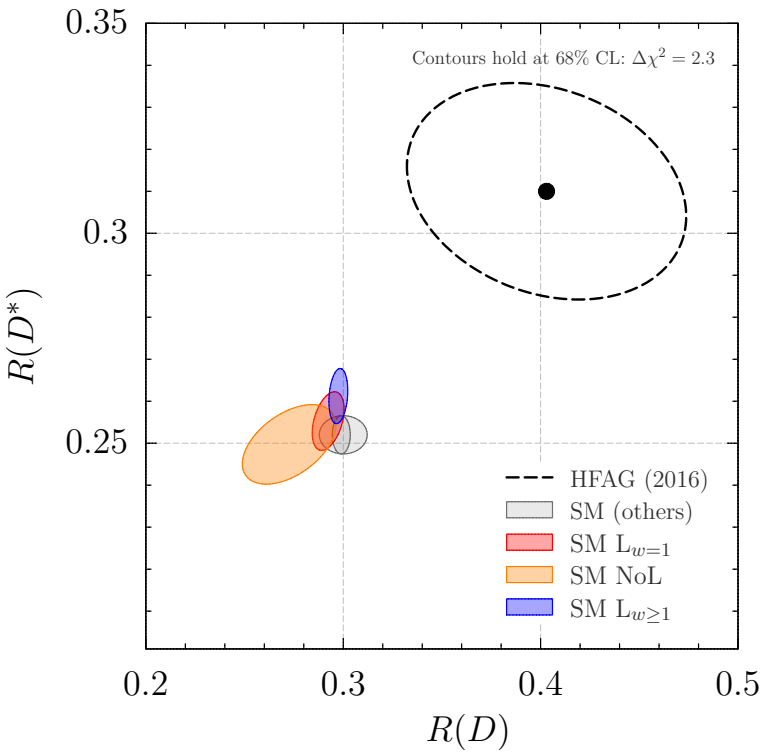
[A. J. Schwartz' talk]

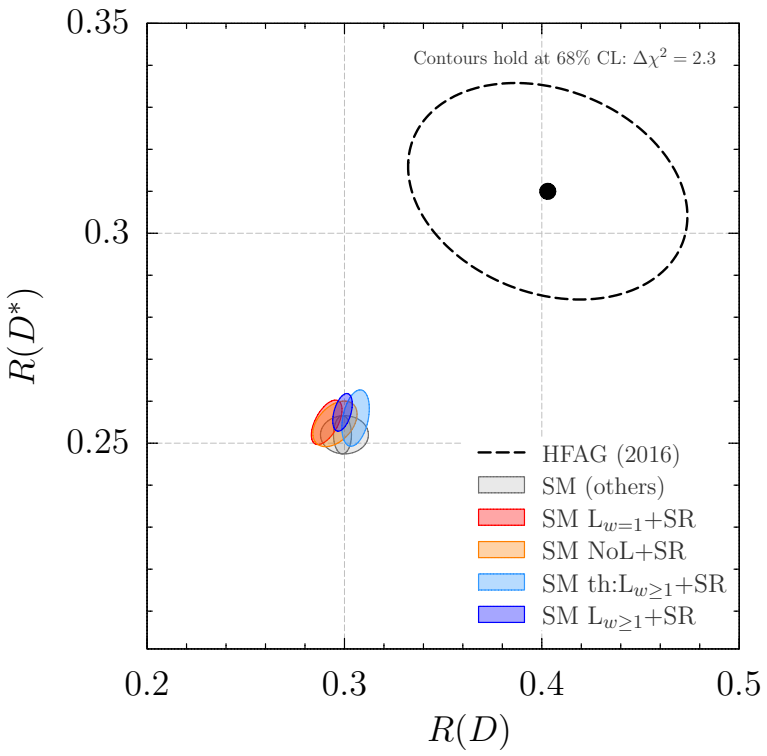
- polarizations/asymmetries in final states can help discriminate operators
  [1206.3760, 1302.7031, 1602.07671, ...]
  - new efficient reweighting tools can help fit these [HAMMER; Ligeti, Papucci, Robinson, 1610.02045]
- not the focus here

see B. Hamilton's talk

Exclusive theory predictions

- recent refit of global data to HQET predictions
  - all $\Lambda_{\rm QCD}/m_b$ form factor corrections included
  - various lattice/sum rule-constrained fits considered





- significance of tension stable across fits — affect op. fits at $O(1\sigma)$ however

[Bernlocher, Ligeti, Papucci, Robinson, 1703.05330]

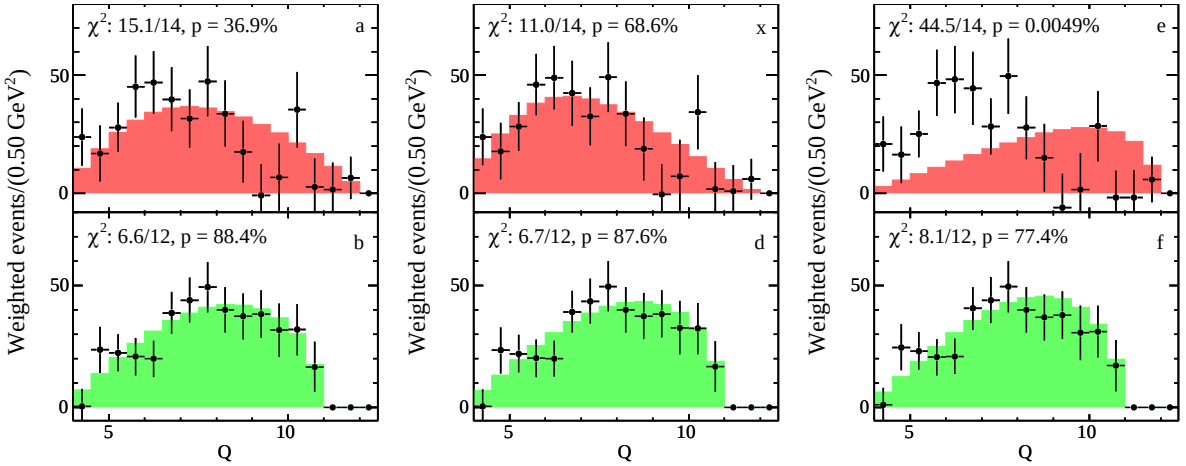
Redundant four-fermion operator analysis

- Large effect (20% of tree-level SM process) suggests tree-level NP
- Fit to different fermion orderings convenient to understand allowed mediators

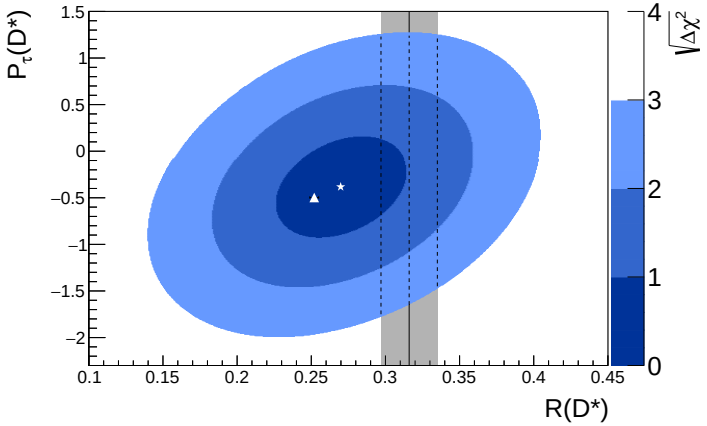
	Operator		Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L) W'_\mu$
$\mathcal{O}_{V_R}$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

- $\mathcal{O}_i$ parametrize all possible dim-6 contributions, $\mathcal{O}'_i$, $\mathcal{O}''_i$ related by Fierz identities
- $\delta\mathcal{L}_{\text{int}}$ only for dim-6 gauge-inv. $\mathcal{O}$s with mediator spin ≤ 1

Constraints beyond rates



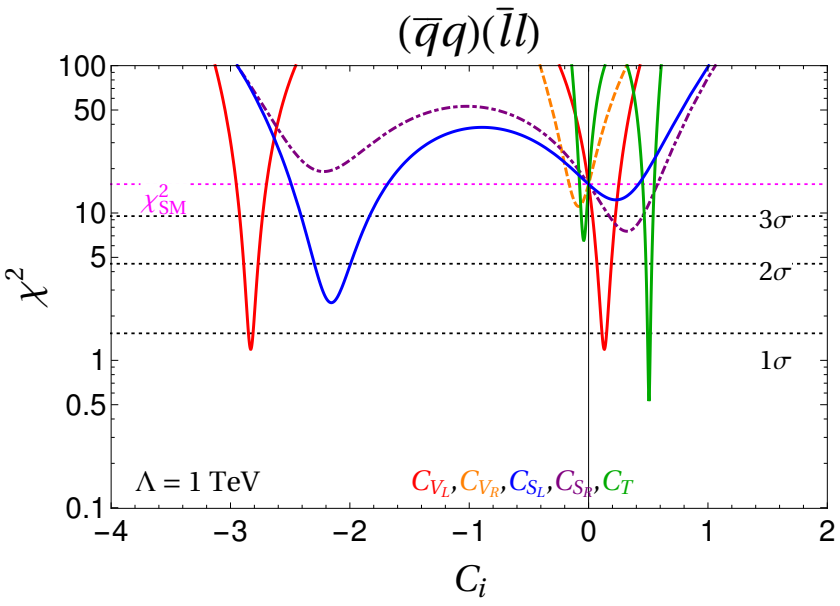
[BaBar, 1303.0571]



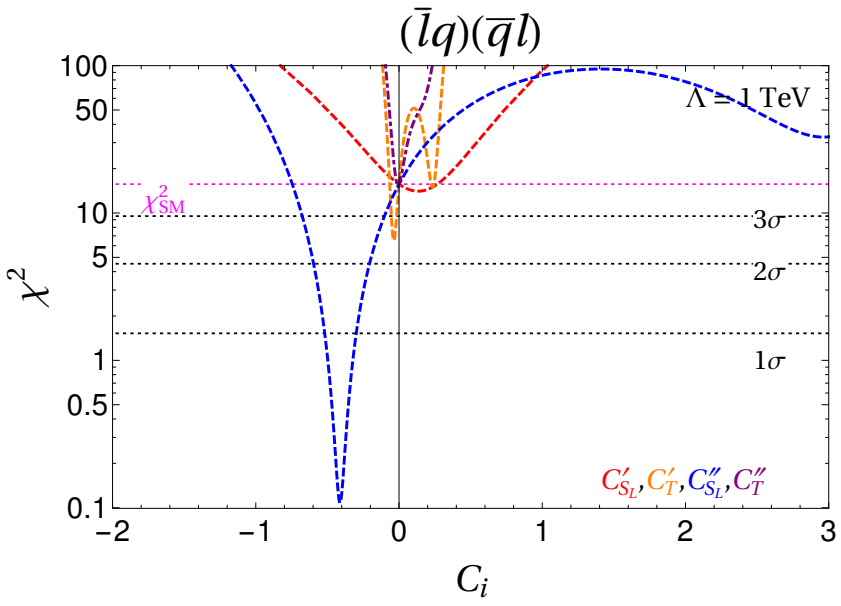
[Belle, 1612.00529]

- BaBar q^2 spectrum known
- (non observation of) $B_c \to \tau^+\nu$ [1605.09308,1611.06676]
  - Both particularly sensitive to scalar $\mathcal{O}$s
- Belle average P_τ in $R(D^*)$
  - no other distributions publicly available
    (preliminary Belle $P_\tau(q^2)$ never published)

Single operator fits



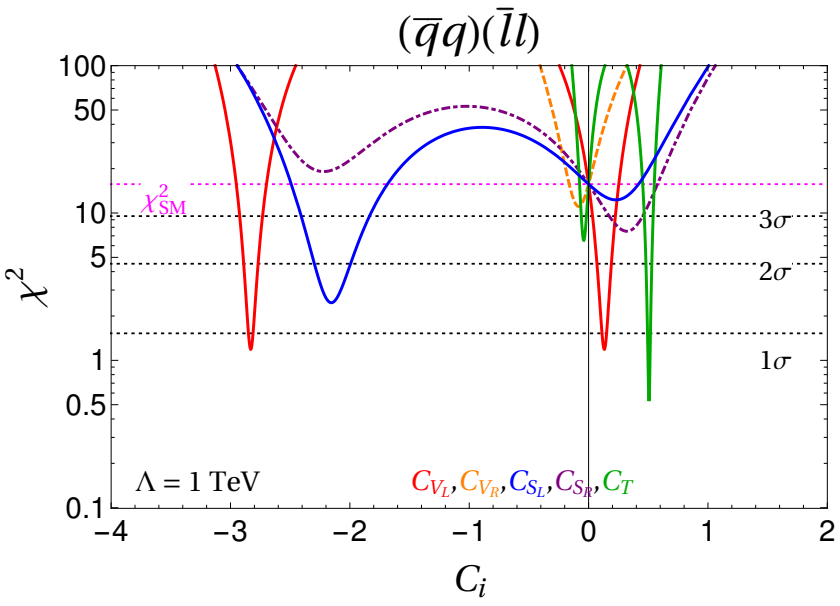
canonical 5 $\mathcal{O}$ operators



non-rescalable $\mathcal{O}'$ and $\mathcal{O}''$ ones

Update of [MF, Ligeti, Ruderman, 1506.08896]

Single operator fits



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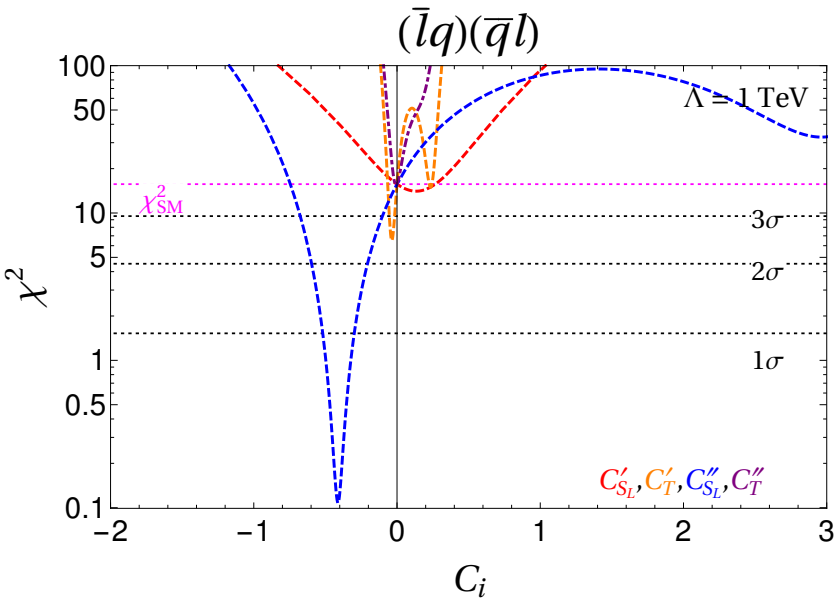


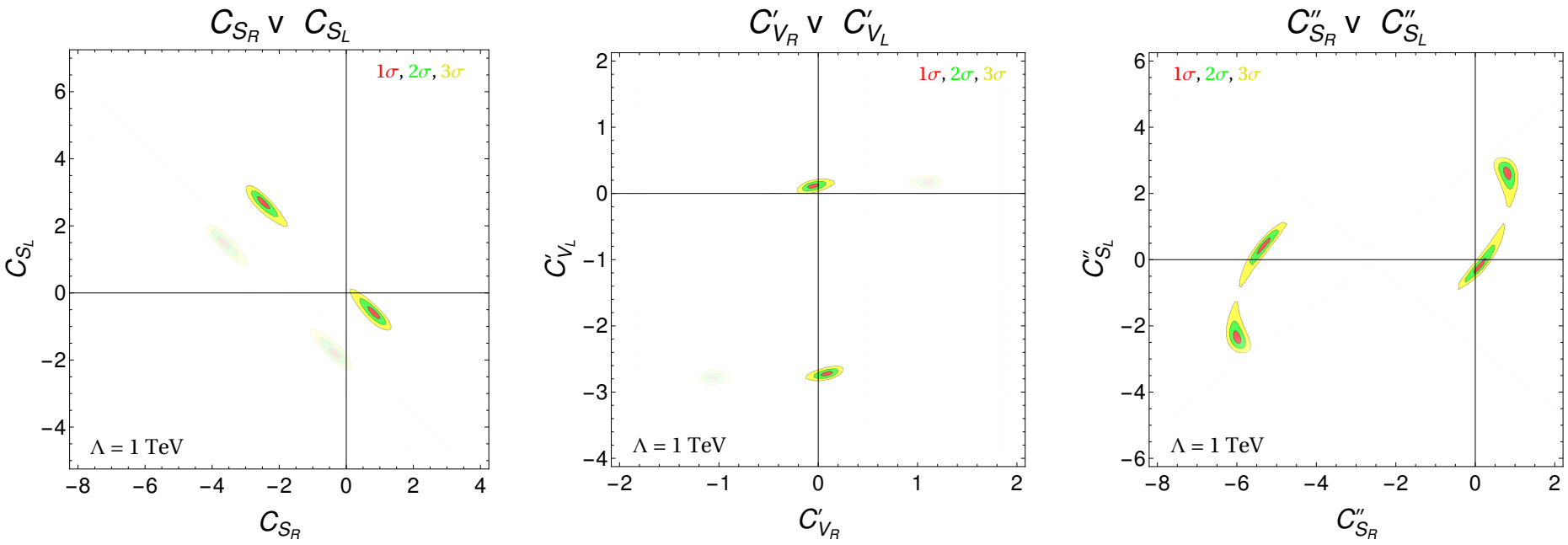
non-rescalable $\mathcal{O}'$ and $\mathcal{O}''$ ones

- C_{S_L} ruled out by q^2 spectra

Update of [MF, Ligeti, Ruderman, 1506.08896]

Two operator fits

- 3 current mediators generate two dim-6 operators at once



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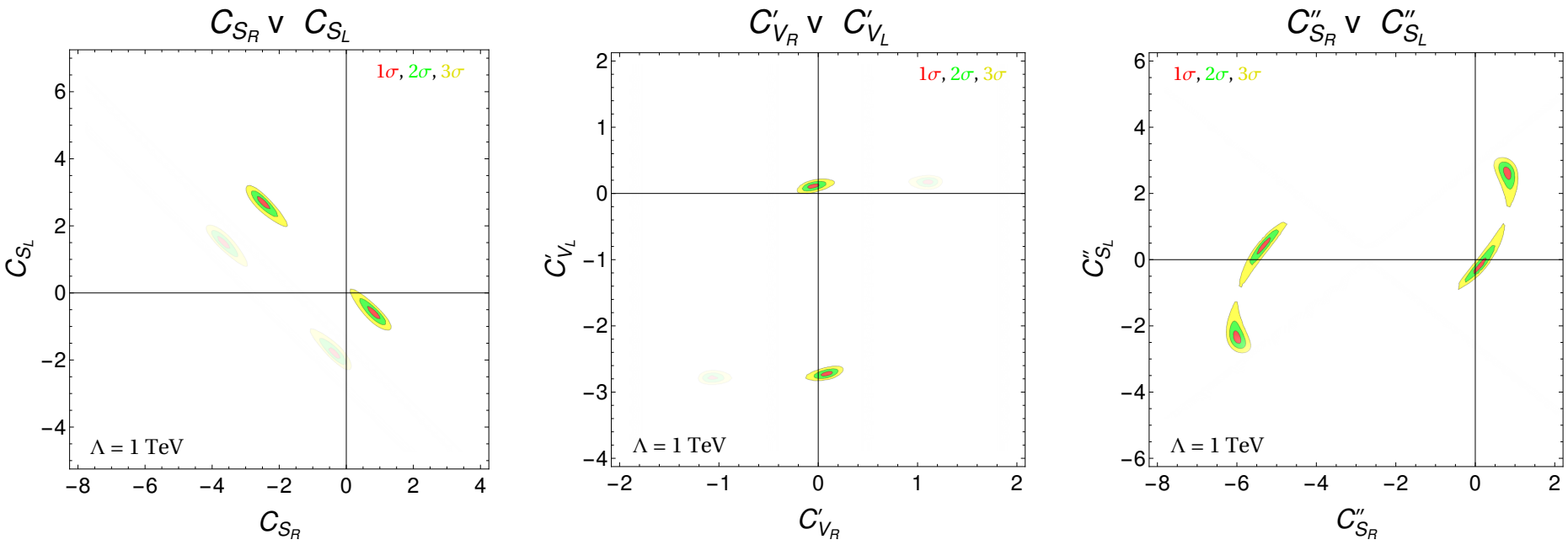
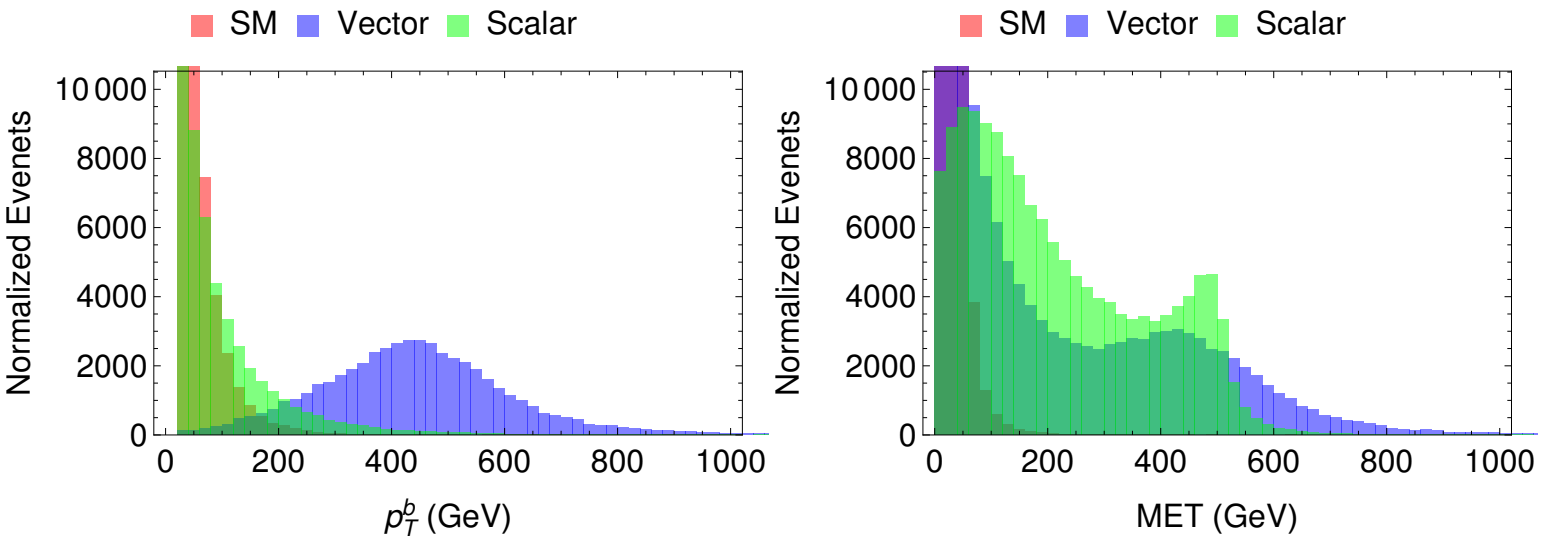


- all C_{S_i} and large C'_{V_R} ruled out by B_c and sometimes q^2 spectra
- large C''_{S_L} ruled our by B_c

Update of [MF, Ligeti, Ruderman, 1506.08896]

Testing $\mathcal{O}_{V_L}$ at the LHC

- all viable fits primarily due to rescaling of SM $\mathcal{O}_{V_L}$ (or equivalent)
- will contribute to $cg \to b\tau\bar{\nu}$
  - and $ug \to b\tau\bar{\nu}$ — flavor symmetry dependent, but otherwise UV-completion agnostic



[Altmannshofer, Dev, Soni, 1704.06659]

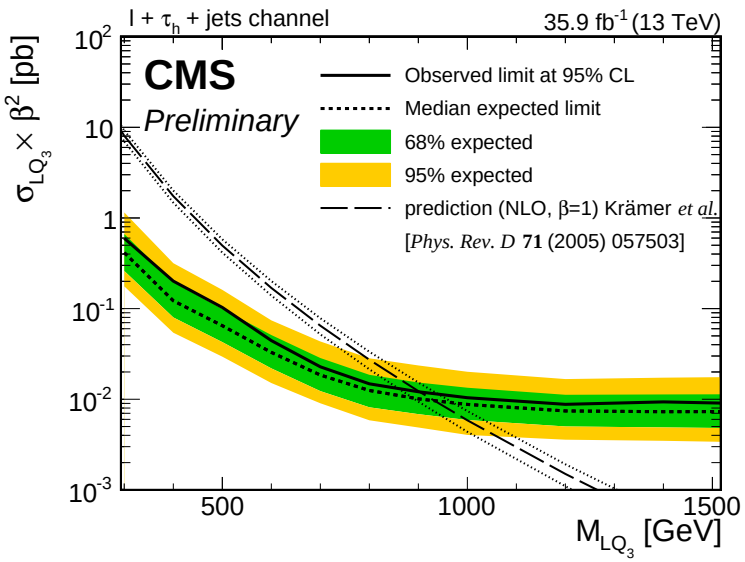
- (reduc.) backgrounds: Wj (mis-ID j), $W \to \tau\nu$ (ISR b), tj (lost j), $b\bar{b}j$ (mis-ID b,j)
- probed at 3σ level at run III, will need HL to say more

Resolving the operators

- need to consider UV origin to say more
- several good fits:
  - W' vector, $(\mathbf{1}, \mathbf{3})_0$
  - "scalar leptoquark", $(\bar{\mathbf{3}}, \mathbf{1} \text{ or } \mathbf{3})_{1/3}$
  - "vector leptoquark", $(\mathbf{3}, \mathbf{1} \text{ or } \mathbf{3})_{2/3}$
- large operator coefficients suggest light*ish* mediators
- non-generic flavor structure necessary to avoid valence q production/decay
- search strategies similar to conventional W', little to add
  - + serious challenges for EW precision once Z' taken into account

LHC LQs
new flavor structures

- LQs are accessible at LHC if $\mathcal{O}$ below unitarity limit
- unavoidable decays:
  - S LQ $\to t\tau$ or $b\nu$
  - U^μ LQ $\to b\tau$ or $t\nu$ (recast $\tilde{t}$ searches)

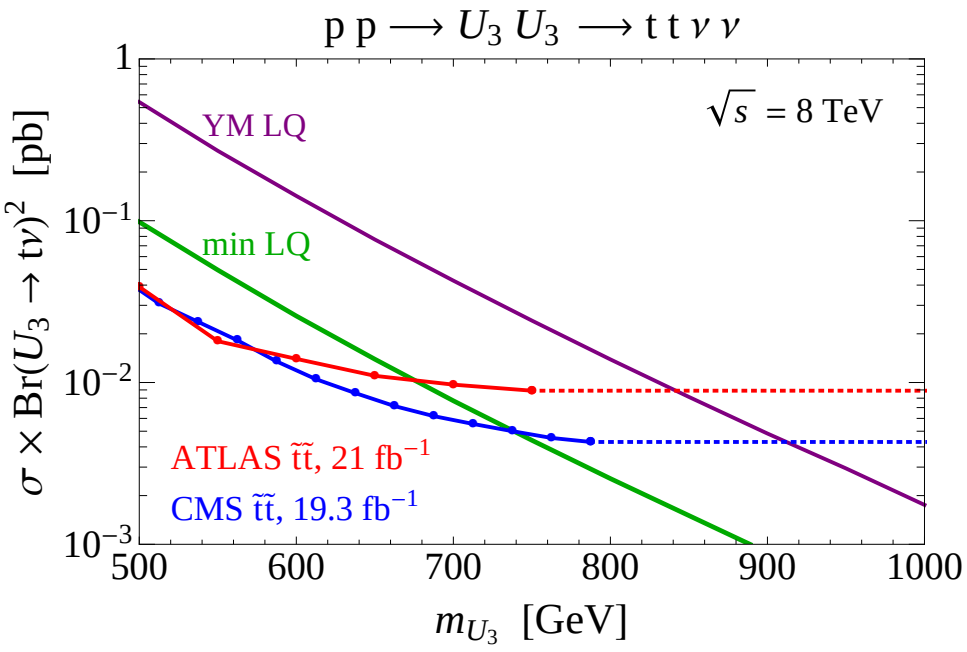


[CMS, 1803.02864]

- current bounds on $m_S \gtrsim 900$ GeV
- $Z \to \tau^+\tau^-$ constraints – leptoquarks via t-channel
  - flavor structure dependent, but usually either not a problem or already ruled out

LHC LQs
vector LQ subtiteties

- $\sigma(U^\mu U^\mu) > \sigma(\tilde{t}\tilde{t})$
- either collaborations must do analysis, or provide data beyond $\tilde{t}$ exclusion limit for recast
  - Ambiguities related to possible "dipole" term $ig_s \kappa U_\mu^\dagger t_{ij}^a U_\nu G_a^{\mu\nu}$
- Now: $m_{U_3} \gtrsim 1050$ GeV, at least
- With HE (maybe HL) will be able to get to unitarity limit

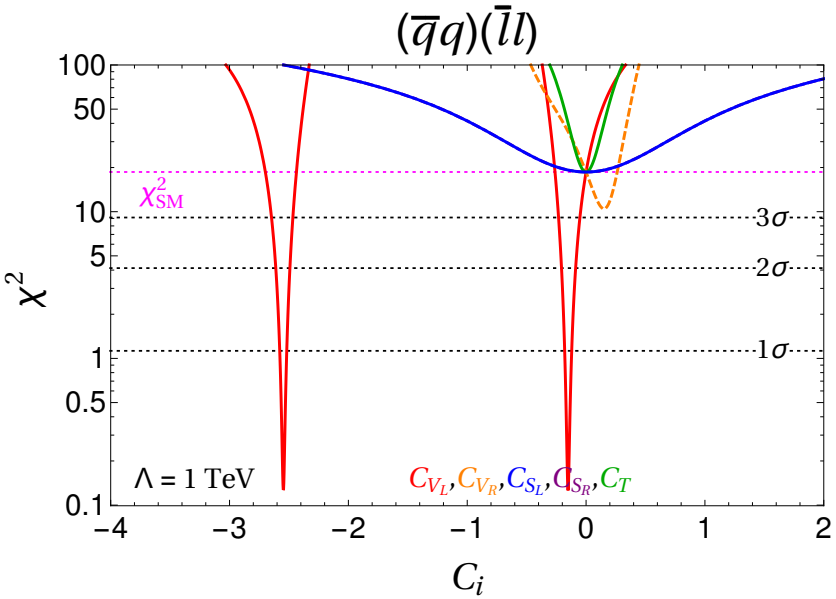


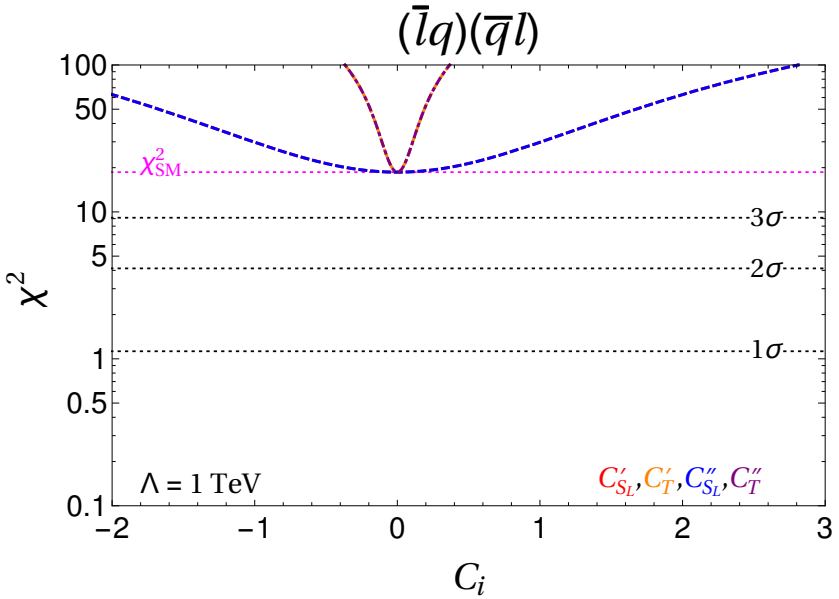
situation 2 eyars ago

Some wilder ideas

Suppress, don't enhance

- (to my knowledge) all NP explanations **enhance** the τ mode compared to the SM
- deviation in ratio of decay rates – **suppress** the e and μ modes instead?
  - operator fits with same structure to τ cases



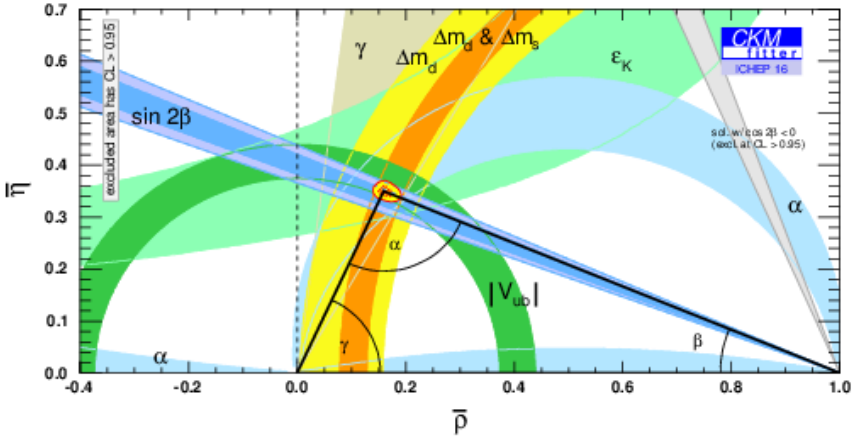


- Only SM four-fermion vector operator viable
  - **scalar/tensor contributions m_ℓ^2 suppressed**

Some wilder ideas

Suppress, don't enhance

- $b \to (c/u)(\mu/e)\bar{\nu}$ modes used for CKM matrix element extraction



$$V_{cb}^{(\mathrm{exp})} \sim 0.9 V_{cb}^{(\mathrm{SM})},$$
$$V_{ub}^{(\mathrm{exp})} \sim 0.9 V_{ub}^{(\mathrm{SM})}$$

- $O(10\%)$ correction to tree-level SM $\Longrightarrow$ refit loop-level unitarity constraints
- strongest constraint is from ϵ_K

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

  - current central values in some tension with such models
  - tension with $R(D^{(*)})$ disappears if data unitarity data moves in 1σ bands
- In principle collider searches can have comparable reach
  - except decays are necessarily mixed generation, not currently bounded
  - full range of LQ decays should be covered Diaz, Schmaltz, Zhong, 1706.05033]

Conclusions

- this ain't how BSM physics was supposed to show up
  - no CKM or loop suppression in SM contribution
- most reasonable BSM explanation points to rescaling of $\mathcal{O}_{V_L}$ for Bs
- mediators must be (HE-)LHC accessible to avoid unitarity limit
  - extensions of existing LHC searches cover much of the parameter space if...
  - range of LQ (and W') channels studied covers full range of flavor scenarios
- combining future low- and high-energy data can tell us what's happening here

Thank you!