Predictions & speculations related to $b \to c\,\tau\bar{\nu}$

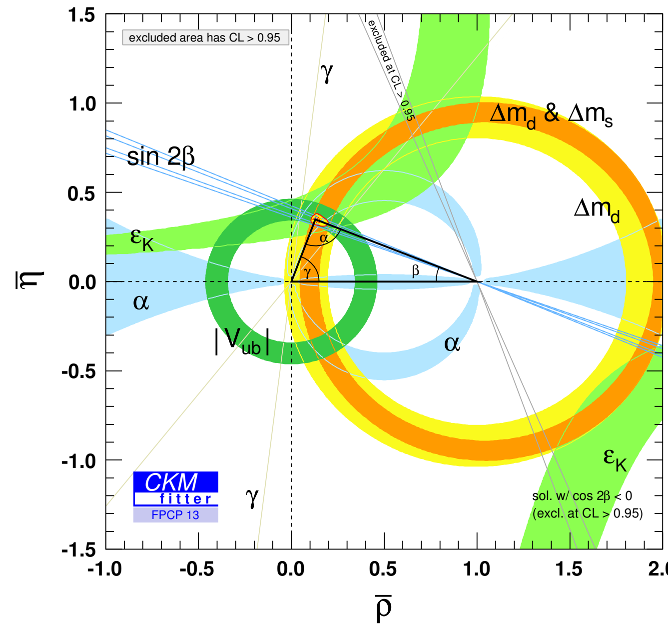
Zoltan Ligeti

See: Freytsis, ZL, Ruderman, to appear

Naturalness @ Weizmann, November 13, 2014

Snapshot of flavor physics

- The level of agreement between the measurements is often misinterpreted
- Much larger allowed region if SM not assumed to hold, more parameters
- $\mathcal{O}(20\%)$ NP contributions to most FCNC (loop dominated) processes are still allowed

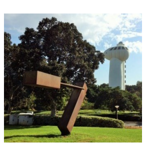


- Future: $$\frac{\text{(LHCb upgrade)}}{(\text{LHCb } 1\,\text{fb}^{-1})} \sim \frac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \frac{\text{(BaBar data set)}}{\text{(CLEO data set)}} \sim 50$$

Last 15 yrs: verify Kobayashi–Maskawa mechanism — Next 15 yrs: discover/study BSM signals?

- Increase in sensitivity to higher scales $\sqrt[4]{50} \sim 2.5$, similar to LHC8 $\to$ LHC14

Expect "unpredictable" progress, too — data usually motivate people to think hard...



The $b \to c\tau\bar{\nu}$ data

The $B \to D^{(*)}\tau\bar{\nu}$ measurements

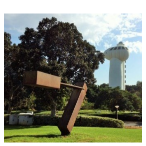
- BaBar reported 3.4σ deviation from SM in the ratios: $R(X) = \dfrac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$

	Belle	BABAR	SM
$R(D)$	0.430 ± 0.091	$0.440 \pm 0.058 \pm 0.042$	0.297 ± 0.017
$R(D^*)$	0.405 ± 0.047	$0.332 \pm 0.024 \pm 0.018$	0.252 ± 0.003
correlation	neglected	-0.27	-

[Watanabe, FPCP 2014 — BaBar 1205.5442 + Belle private combination]

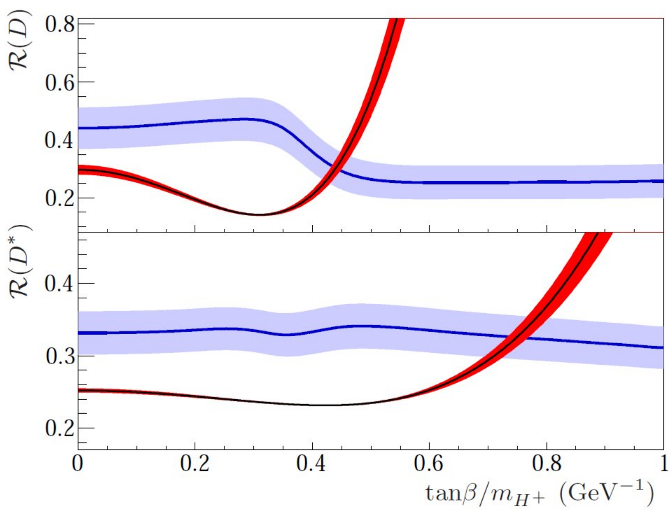
- Public Belle result not yet available with full data, correlation neglected
  Combined significance would only be larger
  [Naive combination, without correlations: $R(D)$: 2.4σ, $R(D^*)$: 3.8σ, $R(D^{(*)})$: 4.8σ]

- SM predictions fairly robust: heavy quark symmetry + lattice QCD

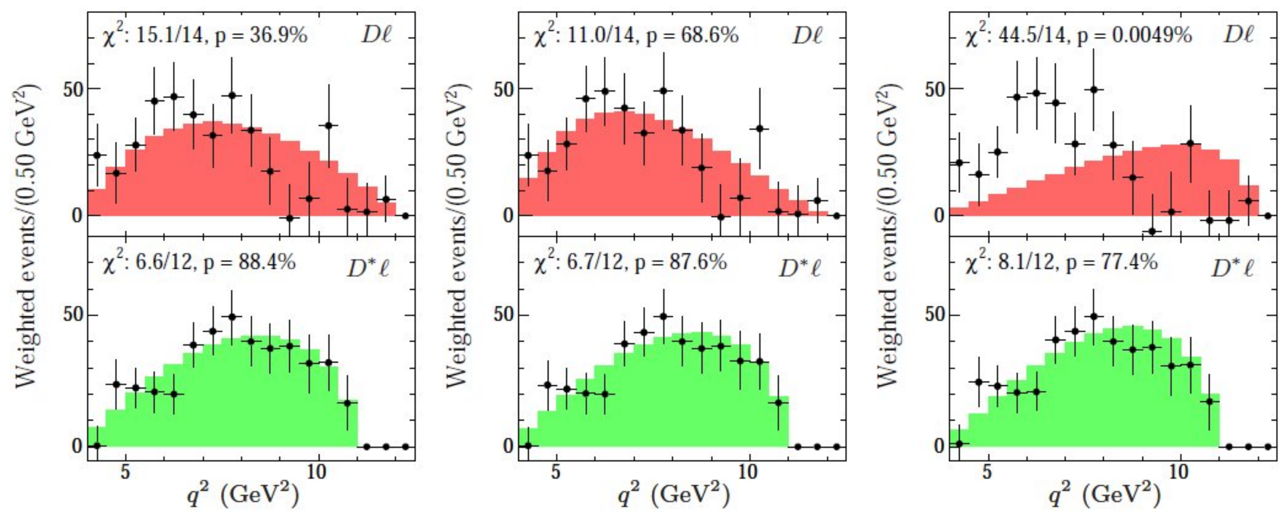


BaBar statements on BSM models

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



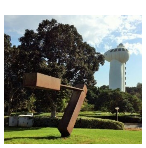
[PRL 109 (2012) 101802, arXiv:1205.5442]



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

- Found that type-II 2HDM gave nearly as bad fit to the data as the SM

$\mathrm{d}\Gamma/\mathrm{d}q^2$ clearly has additional discriminating power



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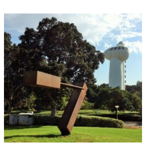
Reasons (not) to take the tension seriously

- B factory measurements with τ leptons are difficult
- Need a large tree-level contribution, SM suppression only by m_τ

  NP expected to show up in FCNCs — need fairly light NP here to fit the data
- Severe constraints on actual models from flavor physics, and from LHC

- Results from BaBar and Belle indicate consistent signal
- Even when BaBar and Belle disagreed in the past, averages often proved robust
- If Nature were as most theorist imagined (until a few years ago), then the LHC (Tevatron, LEP, DM searches) should have already discovered new physics



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Tension with SM is model independent

- Use an OPE-based analysis to constrain SM allowed range as much as possible
- Learn more from inclusive $= \sum$ exclusive

  $\mathcal{B}(B^- \to X_c \ell \bar\nu) = (10.92 {\pm} 0.16)\%$ and $R(X_c) = 0.222 {\pm} 0.003$ [hep-ph/9401226, hep-ph/9811239]

  $\Rightarrow\ \mathcal{B}(B^- \to X_c \tau \bar\nu) = (2.42 \pm 0.05)\%$

  LEP average: $\mathcal{B}(b \to X \tau^+ \nu) = (2.41 \pm 0.23)\%$ [experimental concerns...]

- The $R(D^{(*)})$ data imply:

  $\mathcal{B}(\bar B \to D^* \tau \bar\nu) + \mathcal{B}(\bar B \to D \tau \bar\nu) = (2.78 \pm 0.25)\%$

- Estimate $\mathcal{B}(B \to D^{**} \tau \bar\nu) \gtrsim 0.2\%$ in the SM (the four $1P$ states)
- Thus, tension $\gtrsim 2\sigma$, independent of SM calculation of $R(D^{(*)})$
- Belle II: Expect reduction of uncertainties by factor $8 - 10$

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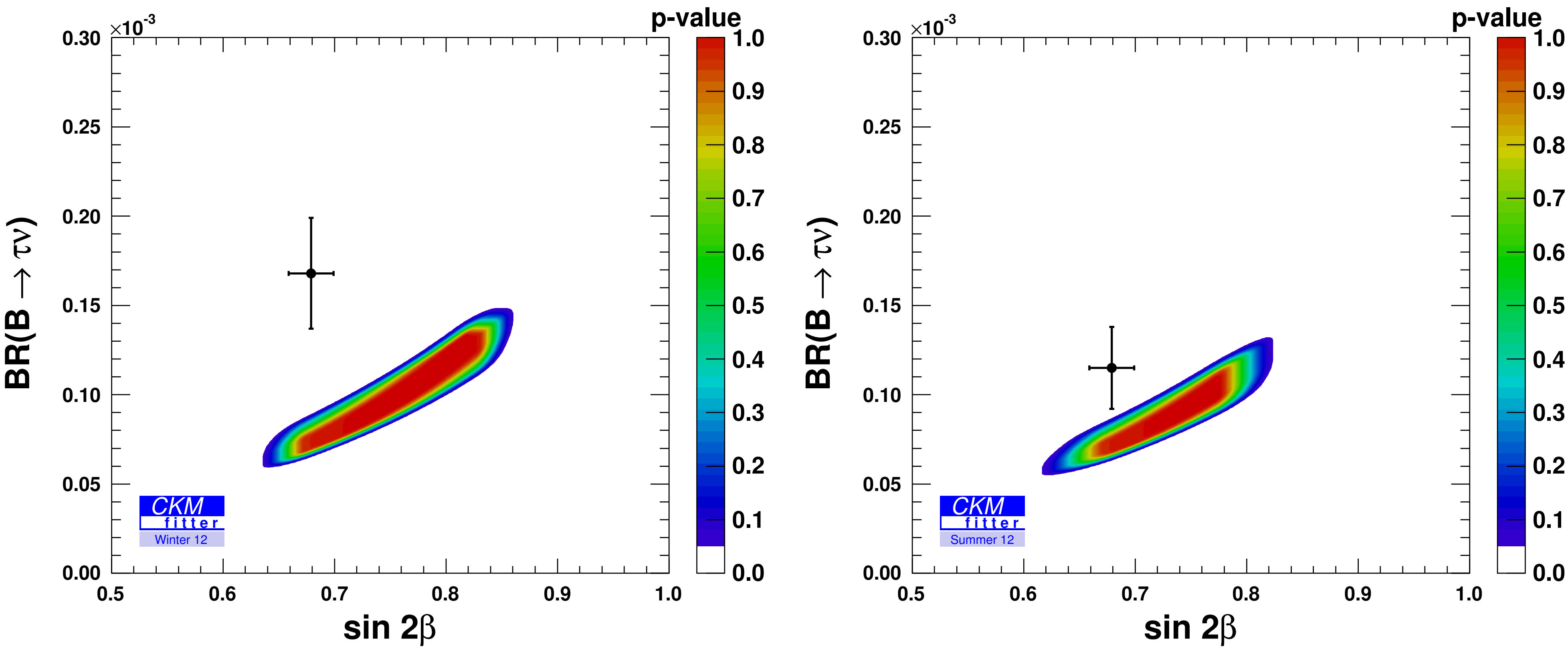
Past tension in $B \to \tau\bar{\nu}$ decay

- Until 2012 there was a $\sim 2.5\sigma$ tension between $\mathcal{B}(B \to \tau\bar{\nu})$ and the CKM fit

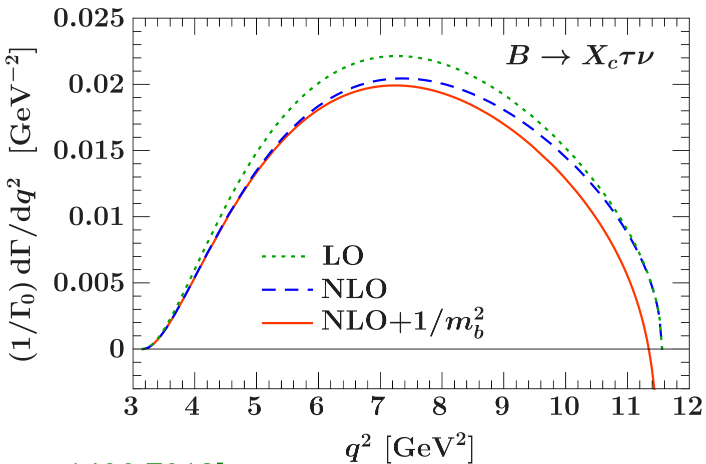


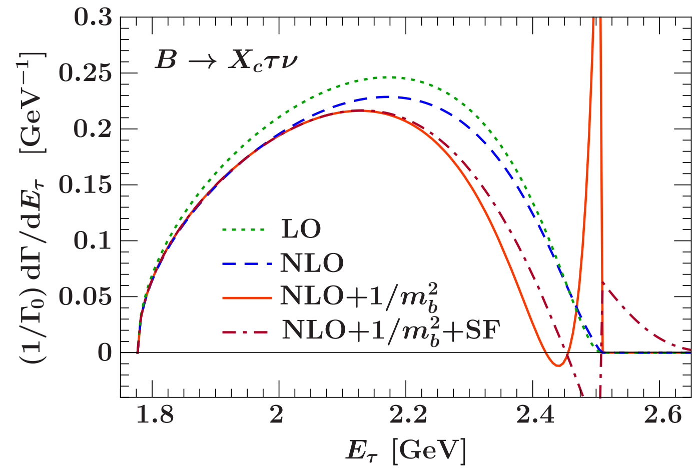
(Or, assuming the SM, $\mathcal{B}(B \to \tau\bar{\nu})$ gave too large $|V_{ub}|$)

Precision $B \to X_c \tau \bar{\nu}$ predictions

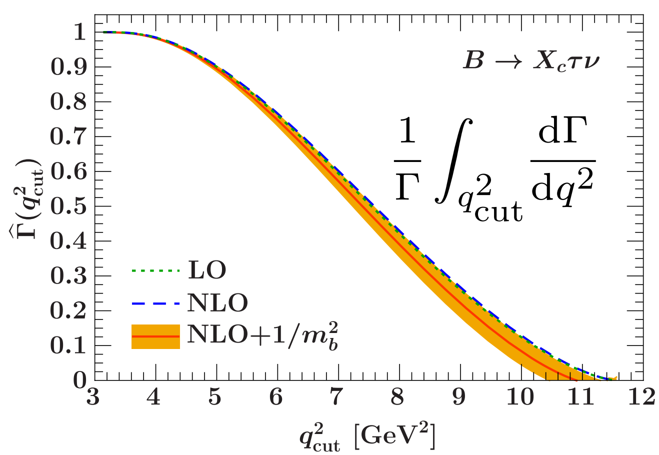
- No measurements since LEP, Belle analysis in progress (No theory work in ~ 15 yrs)

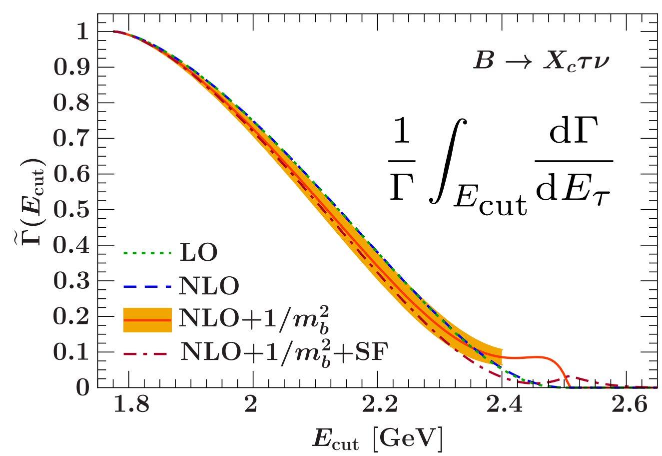
  Papers in '90s used pole mass, did not study spectra (experimentally needed) and uncertainties

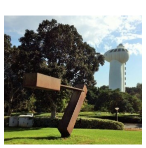




[ZL & Tackmann, 1406.7013]







$B \to X_u \tau \bar\nu$ predictions

- Large interest in Belle II to study all decay modes with τ-s

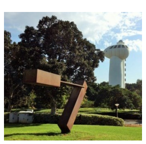
  If LEP could measure $B \to X_c \tau \bar\nu$ with a few $\times 10^6$ $B - \overline{B}$ pairs, surely Belle II can measure $B \to X_u \tau \bar\nu$ with 5×10^{10} $B - \overline{B}$ pairs...

- Suppression of τ mode smaller in $b \to u$: $\Gamma(B \to X_u \ell \bar\nu)/\Gamma(B \to X_u \tau \bar\nu) \simeq 3.0$

  $\Gamma(B \to X_c \ell \bar\nu)/\Gamma(B \to X_c \tau \bar\nu) \simeq 4.5$

- The inclusive calculation is unavailable for any distribution (except for total rate)

  Calculated rates, figuring out subtleties with shape function... [ZL & Tackmann, to appear]

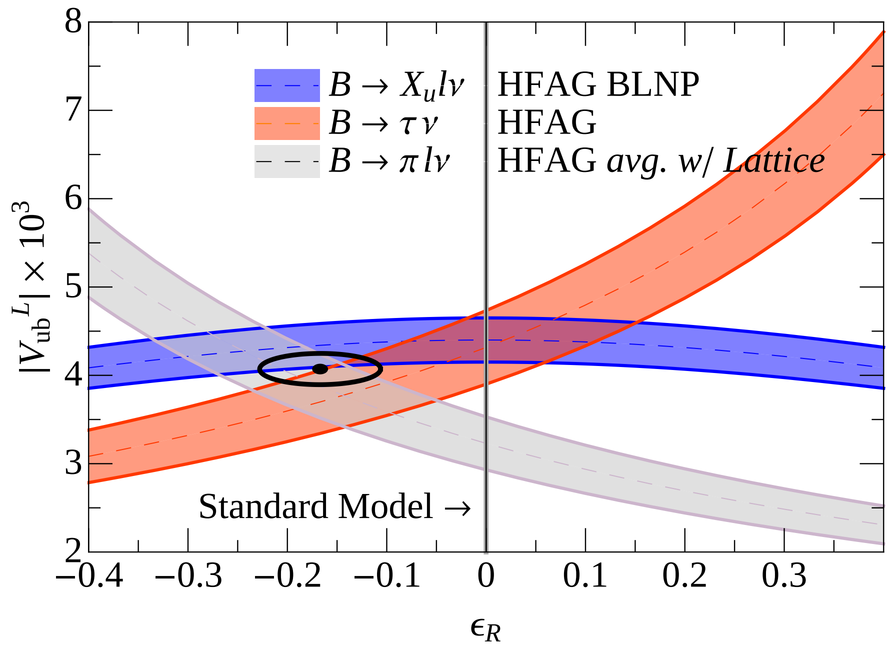


Tensions in $|V_{ub}|$ determinations

- $\sim 3\,\sigma$ tension among $|V_{ub}|$ measurements

Tim Gershon @ FPCP 2014: “Understanding this will involve a great deal of effort, but is essential for continued progress in the field”

- Too early to conclude:
  - Inclusive determination can improve
  - Exclusive measured better with full reco
  - Lattice QCD results will improve



[Bernlochner, ZL, Turczyk, 1408.2516]

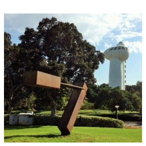
- A BSM possibility:

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \,(\bar{u}\gamma_\mu P_L b + \epsilon_R\, \bar{u}\gamma_\mu P_R b)(\bar{\nu}_\ell \gamma^\mu P_L \ell)$$

Can we construct observables which give “more vertical” constraints?

Decay	$\lvert V_{ub}\rvert \times 10^4$	adm.
$B \to \pi\, \ell\, \bar{\nu}_\ell$	3.23 ± 0.30	$(1+\epsilon_R)$
$B \to X_u\, \ell\, \bar{\nu}_\ell$	4.39 ± 0.21	$\sqrt{1+\epsilon_R^2}$
$B \to \tau\, \bar{\nu}_\tau$	4.32 ± 0.42	$(1-\epsilon_R)$

- NB: Cleanest $|V_{ub}|$ I know, only isospin, $\mathcal{B}(B_u \to \ell\bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-)$ — run LHCb @ 33 TeV



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Operator analysis

Four-fermion operators

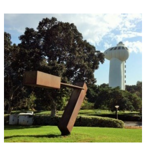
- Parametrize new physics:

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}}\, V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$$

  Consider redundant operators with different fermion ordering — simplifies understanding the mediators (which are integrated out)

  Need substantial correction to SM tree-level process $\Rightarrow$ forget about NP in loops

- Each ordering is convenient for a particular type of mediator
  Simplifies fits to all possible gauge invariant operators generating $b \to c\tau\bar{\nu}$

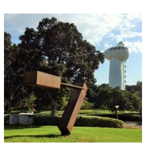


Operators convenient to consider

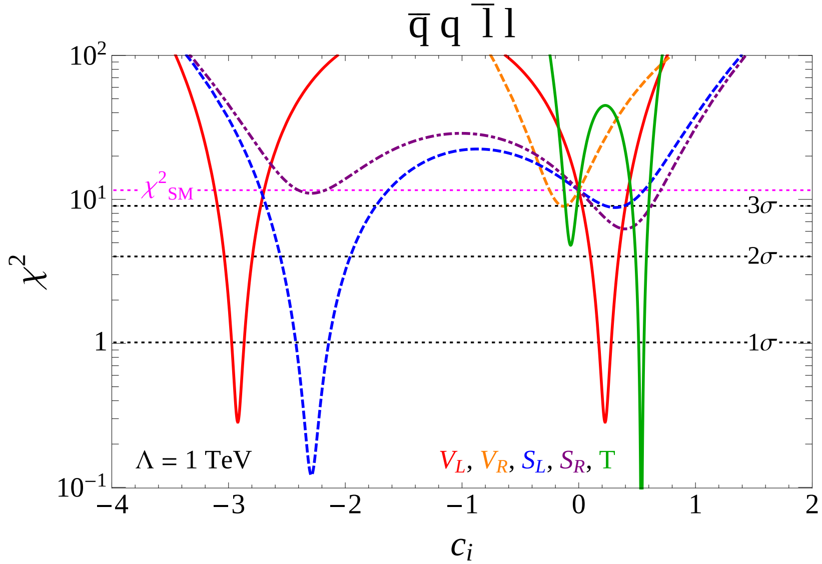
- Redundant set of operators, simplifies understanding of models:

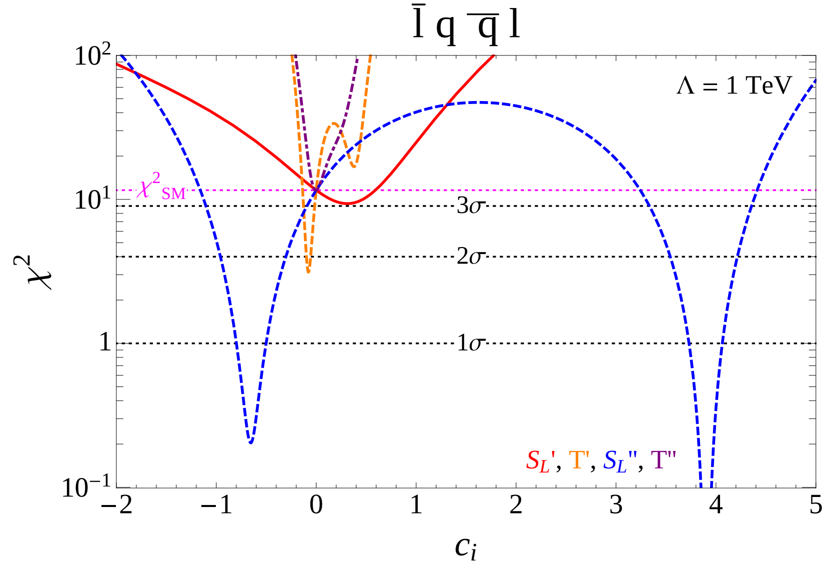
	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(1,3)_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu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

(Usually only the first 5 operators are considered)



Fits for a single operator





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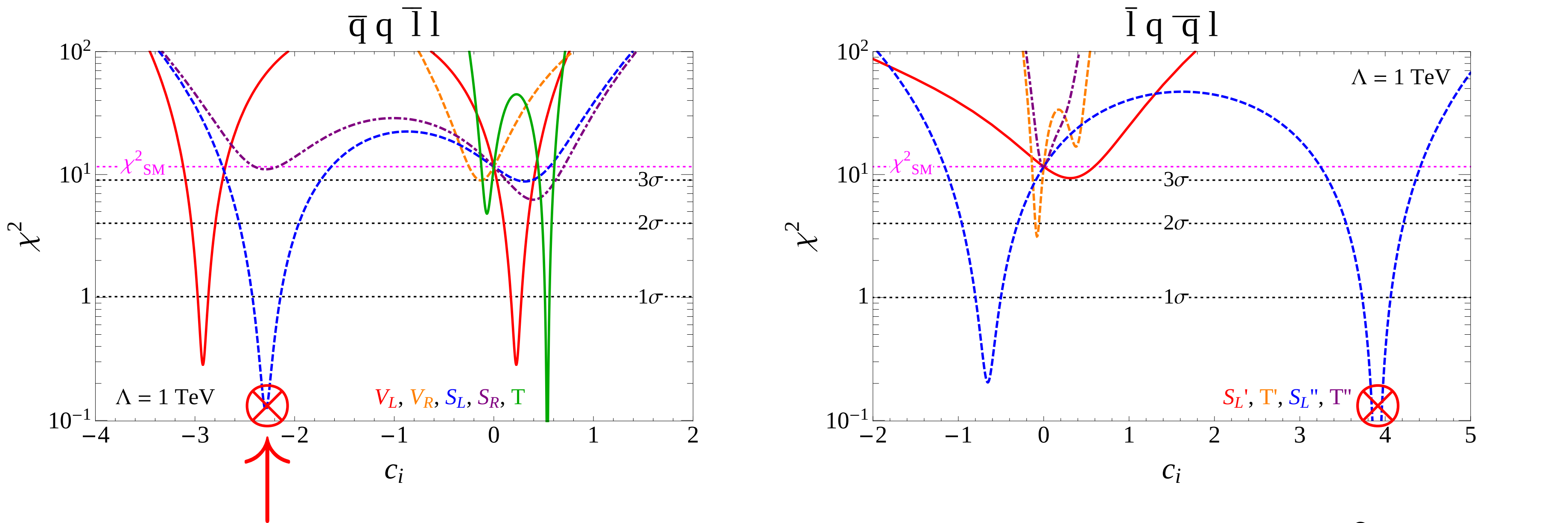


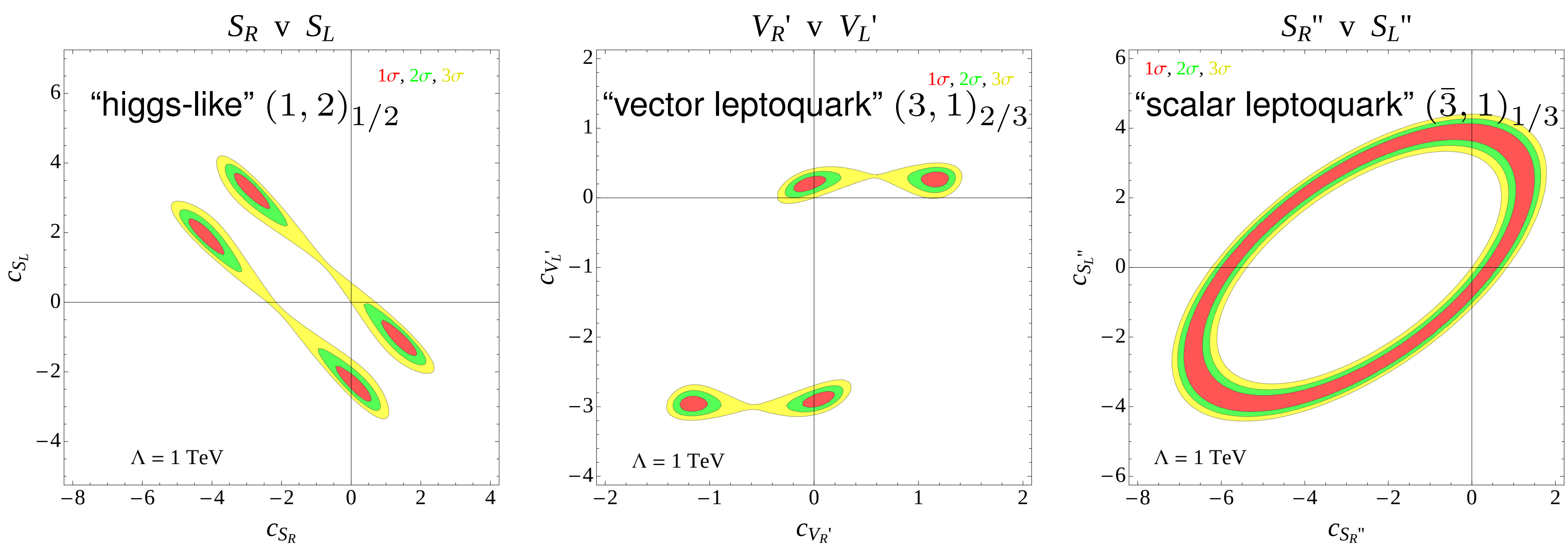
[BaBar, 1303.0571]

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

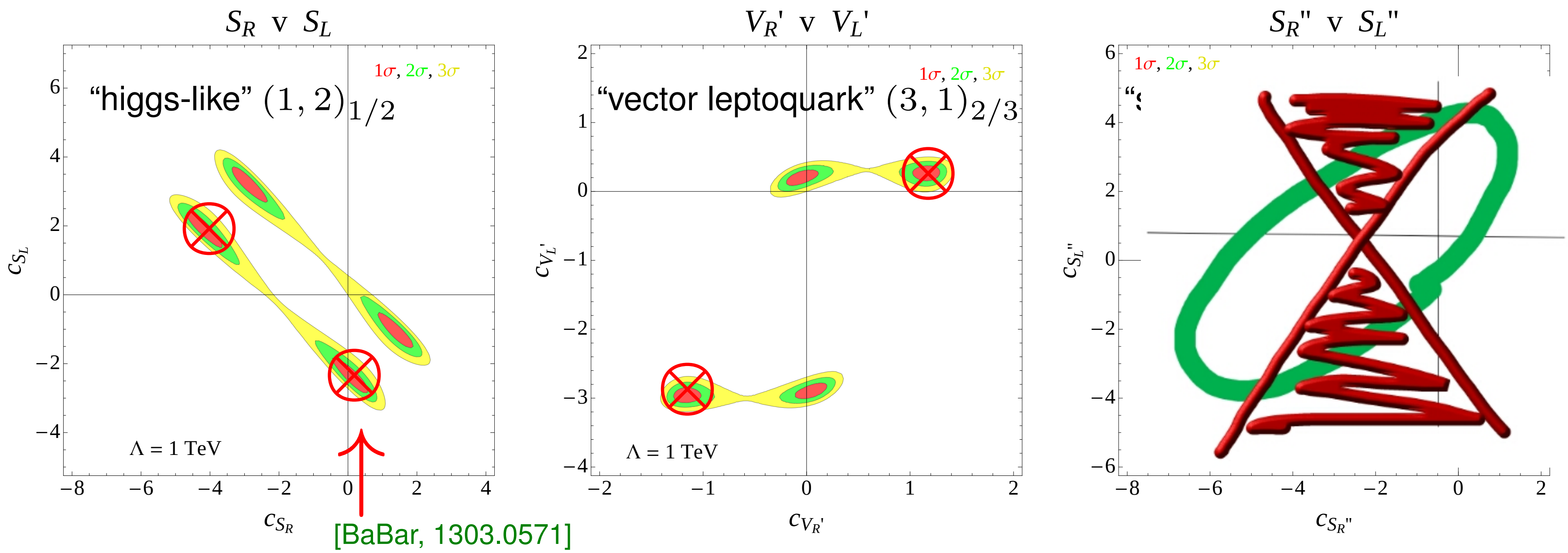
- We rederived everything from scratch (beware of mis-Fierzing in some papers)

  Agree (up to minor typos) with “classic” paper: Goldberger [hep-ph/9902311]

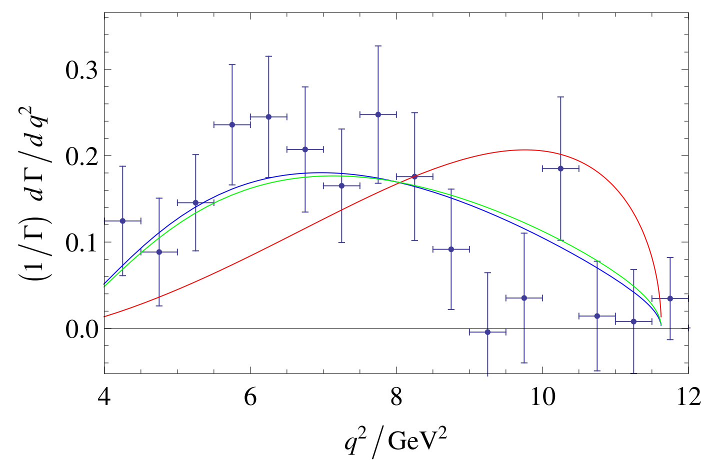
Fits for two operators

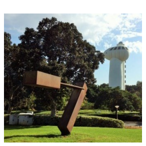


Fits for two operators



Operator coefficients	
$C'_{V_L} = 0.2$	$C'_{V_R} = 1.2$
$C'_{V_L} = 0.2$	$C'_{V_R} = -0.02$
$C''_{S_R} = 0.27$	$C''_{S_L} = -0.27$





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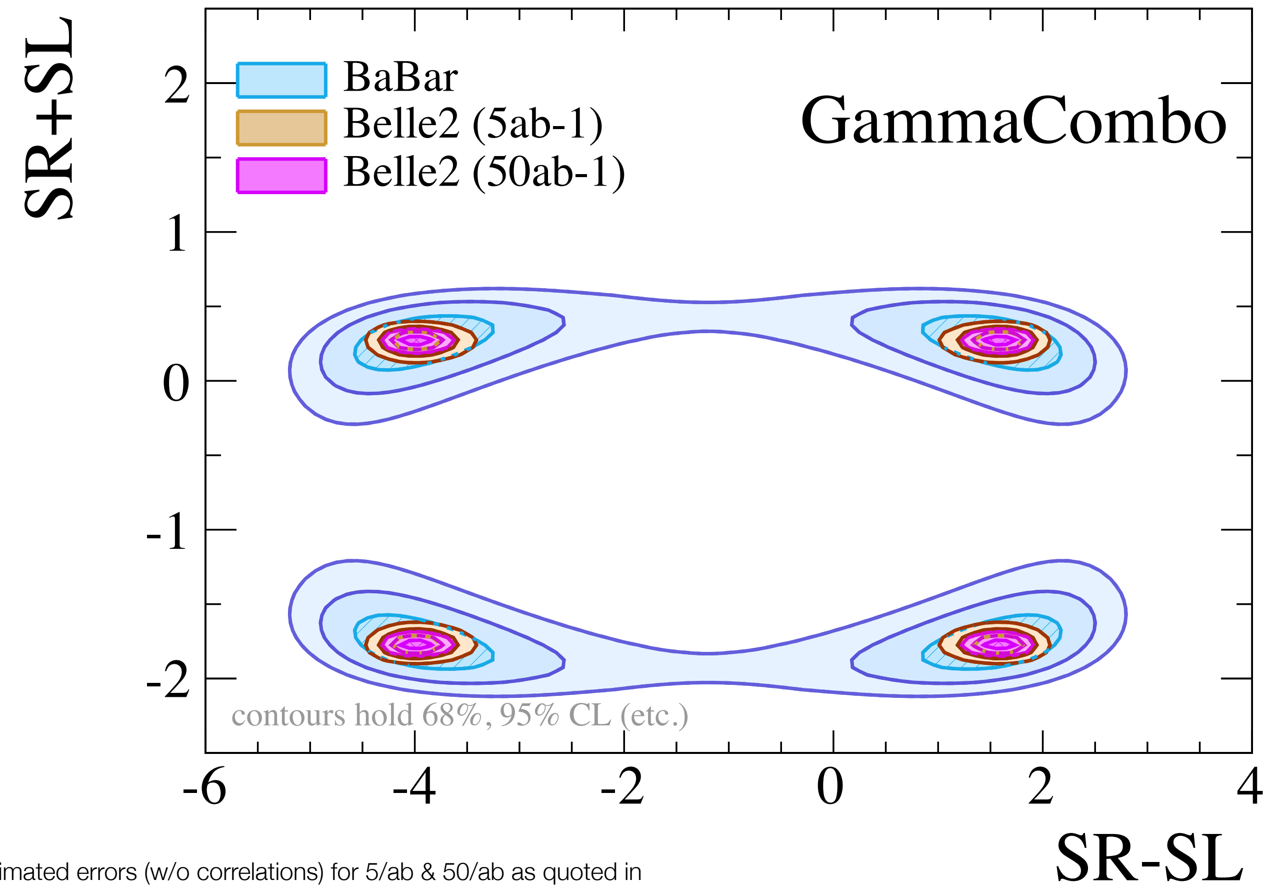
Future sensitivity — a rough estimate

Belle2 with 5/ab & 50/ab



Using estimated errors (w/o correlations) for 5/ab & 50/ab as quoted in
https://belle2.cc.kek.jp/~twiki/pub/Public/B2TIP/SuperKEKBReport.pdf

[Bernlochner @ B2TIP]

Flavor symmetries for $b \to c\tau\bar{\nu}$

Viable mediators

- 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 $(3,3)_{2/3}$

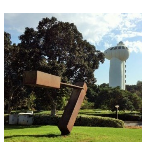
- Surprising if only BSM operator had $(\bar{b}c)(\bar{\tau}\nu)$ flavor structure

  Consider MFV and $U(2)^3$ models / scenarios [Fajfer, Kamenik, Nisandzic, Zupan, 1206.1872]

- Focus on quark flavor, assume only coupling to τ
  This is an assumption in the MFV case, more natural in $U(2)^3$ models

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

- Enough to eliminate some scenarios



Eliminating "W'-like" and "Higgs-like" models

- A vector mediator with W' quantum numbers has to be a flavor singlet to couple to both quark and lepton pairs

  $\Rightarrow$ Couplings to lighter generations cannot be suppressed

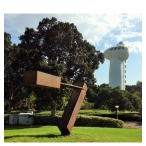
  $\Rightarrow$ Collider limits exclude such models by orders of magnitude

- Similar to the W', a scalar must be a flavor singlet to have all necessary couplings

  $\Rightarrow$ Must have coupling ratios to different flavors like a (charged) Higgs

  $\Rightarrow$ $D - \overline{D}$ mixing data excludes observed $B \to D^{(*)}\tau\bar{\nu}$ excess

- Left with models with leptoquark quantum numbers



MFV leptoquarks

- Assign charges under:

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

- Possible choices:

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

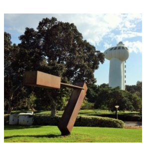
$$\text{vectors: } U_\mu \sim (\mathbf{3},\mathbf{1},\mathbf{1})\,, \quad (\mathbf{1},\mathbf{3},\mathbf{1})\,, \quad (\mathbf{1},\mathbf{1},\mathbf{3})$$

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

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

  Both can be electroweak singlets or triplets



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

- Interactions terms for electroweak singlet:

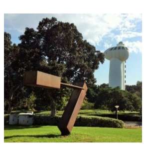
$$
\begin{aligned}
\mathcal{L} &= S(\lambda Y_d^\dagger\, \bar{q}_L^c i\tau_2 \ell_L + \tilde{\lambda} Y_d^\dagger Y_u\, \bar{u}_R^c e_R) \\
&= S_i(\lambda y_{d_i} V_{ji}^*\, \bar{u}_{Lj}^c e_L - \lambda y_{d_i} \bar{d}_{Li}^c \nu_L + \tilde{\lambda} y_{d_i} y_{u_j} V_{ji}^*\, \bar{u}_{Rj}^c e_R)
\end{aligned}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

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 iff $y_b = \mathcal{O}(1)$



The $U_\mu(1,1,3)$ Lagrangians

- Interactions terms for electroweak singlet:

$$\begin{aligned}\mathcal{L} &= (\lambda\, \bar{q}_L Y_d \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R)\, U^\mu \\ &= (\lambda y_{d_i} V_{ji}\, \bar{u}_{Lj} \gamma_\mu \nu_L + \lambda y_{d_i} \bar{d}_{Li} \gamma_\mu \tau_L + \tilde{\lambda} \bar{d}_{Ri} \gamma_\mu \tau_R)\, U_i^\mu\end{aligned}$$

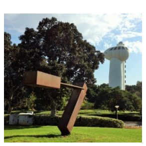
  As before, contribution to $R(X_c)$ via: $(m_{U_3} \neq m_{U_1} = m_{U_2})$

$$\frac{V_{cb}}{m_{U_3}^2} \Big(\lambda^2 y_b^2\, \mathcal{O}'_{V_L} + \lambda \tilde{\lambda} y_b\, \mathcal{O}'_{V_R}\Big)$$

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

- Can fit $R(D^{(*)})$ data iff $y_b = \mathcal{O}(1)$

[NB: vector leptoquarks are hard to make sense of as a low energy effective theory, without knowing the UV completion — divergences]



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

- With three Yukawa spurion insertions, can write:

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

- Leads to operators of the form:

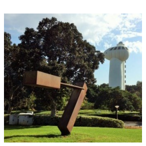
$$\frac{V_{tb}^* V_{ts}}{2m_{S_3}^2} \, y_t^2 y_b^2 \, \lambda' \lambda \, (\bar{b}_L \gamma^\mu s_L \, \bar{\nu}_L \gamma_\mu \nu_L)$$

- Current limits from $B \to K\nu\bar{\nu}$ require:

$$\lambda'/\lambda \lesssim 0.07$$

- A vector singlet is the only one of the four leptoquarks without such a 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)



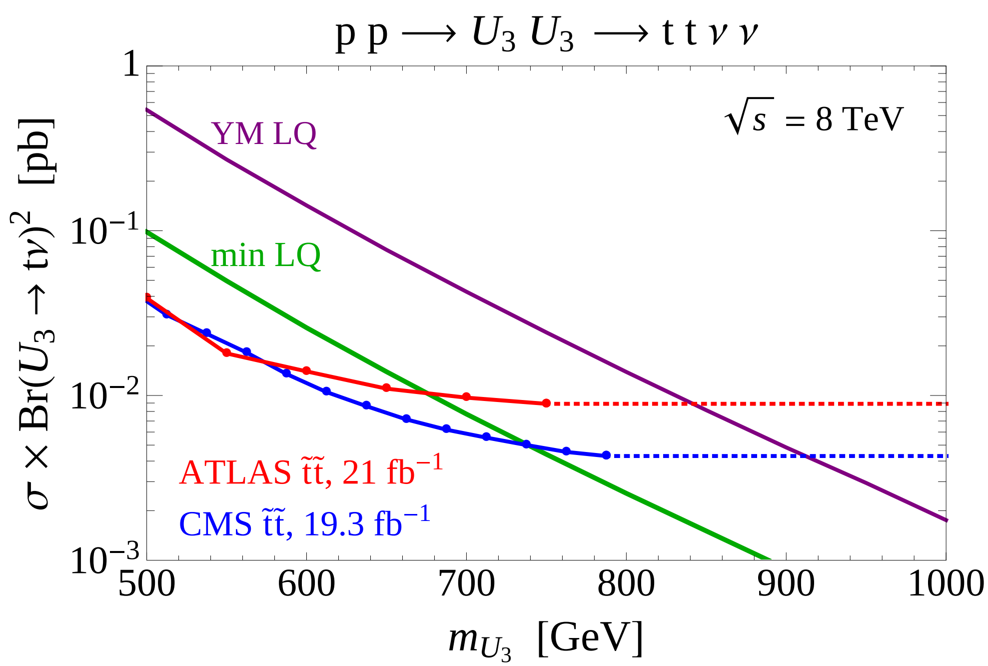
$U_\mu(1,1,3)$ — LHC constraints

- The $\tilde\lambda$ term for electroweak singlet vector leptoquark gives unsuppressed coupling to 1st generation
$\Rightarrow$ constraints from t-channel exchange in $pp \to \tau^+\tau^-$ $\Rightarrow$ $\tilde\lambda \lesssim 0.15\,\lambda$

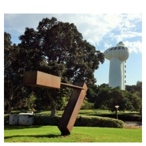
- Limits on m_{U_3} from direct leptoquark search ($b\tau$) or recasting stop ($t\nu$) searches:

Ambiguities related to possible “dipole” term: $-ig_s\kappa\, U_\mu^{i\dagger} t_{ij}^a U_\nu^j\, G_a^{\mu\nu}$

Find: $m_{U_3} \gtrsim 750$ GeV



- For S, CMS search for third generation scalar LQ decaying to $t\tau$ gives $m_{S_3} \gtrsim 500\,\mathrm{GeV}$ [CMS-PAS-EXO-13-010]



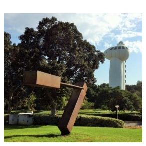
Additional constraints

- Main constraints from loop processes: (i) meson mixings, and (ii) electroweak precision corrections to $R(Z \to \tau^+\tau^-)$ and $A(Z \to \tau^+\tau^-)$

  Scalar LQ calculable, for vector LQ need prescription for UV divergence of loops

  [Jure et al. (1206.1872) dismissed scalar due to PEW constraints, we think there is marginal room]

- Bounds are satisfied, although some constraints are tight

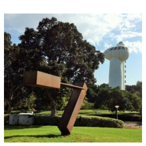


Final comments

Several possible tests & consequences

- LHC: several extensions to current searches would be interesting:
  - Searches for $t\tau$ and $b\tau$ resonances
  - Extensions of stop/sbottom searches to higher prod. cross sections ($t\nu$ and $b\nu$)
  - Searches for states appearing on-shell in t- but not in s-channel in pp collisions
  - Enhanced $h \to \tau^+\tau^-$ rate (and $t \to c\tau^+\tau^-$ [tough])

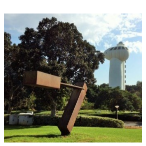
- Low energy probes:
  - Firm up $B \to D^{(*)}\tau\bar\nu$ rate and kinematic distributions; Cross checks w/ inclusive
  - Smaller theor. error in $[\mathrm{d}\Gamma(B \to D^{(*)}\tau\bar\nu)/\mathrm{d}q^2]/[\mathrm{d}\Gamma(B \to D^{(*)}l\bar\nu)/\mathrm{d}q^2]$ at same q^2
  - Improve bounds on $\mathcal{B}(B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



Conclusions

- Amusing if NP shows up in an operator w/o much CKM and loop suppression
- Despite statements in the literature, possible to write down (somewhat) sensible models for $B \to D^{(*)}\tau\bar{\nu}$ excesses, with extensions to other flavors
- Several simple extensions to current LHC searches could cover much of this parameter space (see anomalies or rule out models)
- 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)



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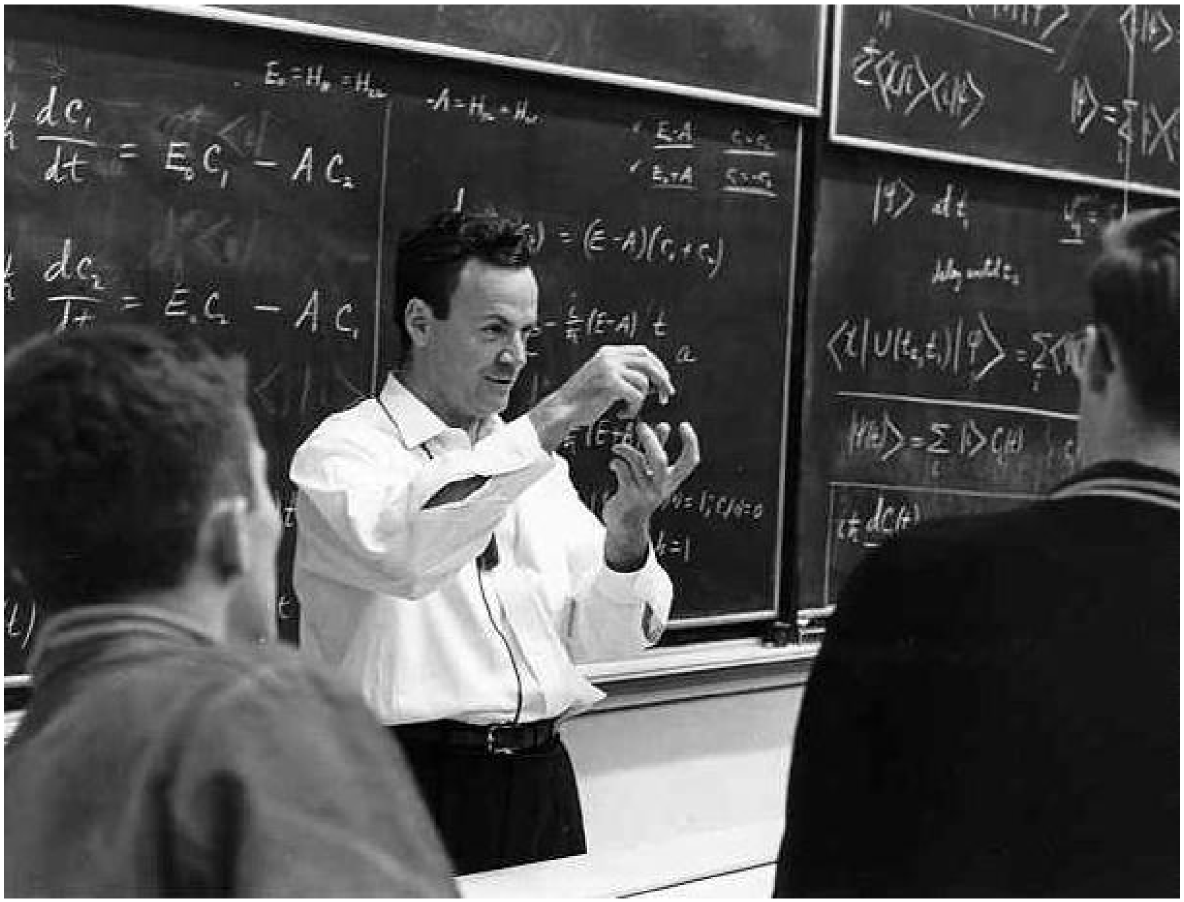
Ultimately, data will tell



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]