The $B \to D^{(*)}\tau\bar{\nu}$ & $B \to \tau\bar{\nu}$ decays,
Theoretical status thereof

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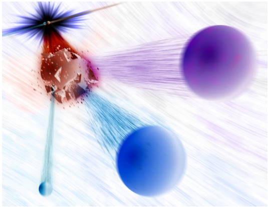


Massive leptons in (semi-)leptonic B decays

unique windows into both NP and the SM via $B \to (X)\tau\bar{\nu}$ decays

- Standard Model
  - $B \to D^{(*)}$ transitions both depend on FFs whose contribution vanishes as $m_\ell \to 0$
  - $B^- \to \tau^-\bar{\nu}$ only decay sensitive to f_B measurable in the near future
- New Physics
  - NP often presumed to couple preferentially to 3rd generation
  - A reason to persue $B \to X_s\nu\bar{\nu}$ and $B_{(s)} \to (X)\tau\tau$ for years
    [Hewitt, hep-ph/9506289; Grossman, Ligeti, Nardi, hep-ph/9510378 & hep-ph/9607473]]
- somewhere in between (focus of most of this talk)
  - high-precision in $B \to X_{u,c}\ell\bar{\nu}$ critical to extraction of $|V_{ub}|$, $|V_{cb}|$
  - ratios are great venue for tests of lepton flavor universality (LFU)

standard diclaimers: . . . general overview, but colored by my biases . . .
. . . apologies to any recent work I might have missed . . .

Plan

- Introduction
- Precise SM predictions
  - complimentary, CKM-parameter-free families of ratio observables for LFU sensitivity
- Quantifying NP sensitivity
  - redundant effective operator bases for identification of UV physics
- NP descriminators
  - more differential distributions for discrimination of scenarios
- Consequences and Conclusions

$B^- \to \tau^- \bar{\nu}$
Pure leptonic decays

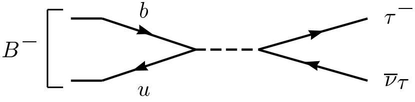
In the SM:

$$\Gamma(B^- \to \tau^- \bar{\nu}) = \frac{|V_{ub}|^2 G_F^2}{8\pi} f_B^2 m_\tau^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2$$

either measure $|V_{ub}| f_B$ in data or use f_B from lattice to extract $|V_{ub}|$
(e.g., latest lattice world average: $f_B = (190.5 \pm 4.2)$ MeV [FLAG, 1310.8555])

- only P-odd currents contribute: $\langle 0 | \bar{b}(\gamma^\mu)\gamma_5 c \,|B\rangle \neq 0$
- new pseudoscalar couplings typically proportional to fermion mass:

$$\Gamma(B^- \to \tau^- \bar{\nu}) = |1 + r_{\text{NP}}|^2 \, \Gamma(B^- \to \tau^- \bar{\nu})_{\text{SM}}$$
$$= |1 + C_A V + m_B^2 C_P|^2 \, \Gamma(B^- \to \tau^- \bar{\nu})_{\text{SM}}$$



$|V_{ub}|$ drops out of ratio, but NP independent of lepton mass

overall rate can still be affected/act as a bound [Hou, PRD48, 2342 (1993)]

$$\frac{\Gamma(B^- \to \tau^- \bar\nu)}{\Gamma(B^- \to \mu^- \bar\nu)} = \frac{\Gamma(B^- \to \tau^- \bar\nu)_{\mathsf{SM}}}{\Gamma(B^- \to \mu^- \bar\nu)_{\mathsf{SM}}}$$

- $B^- \to \mu^- \bar\nu\gamma$ correction complicates situation – no helicity suppression

an alternative: compare to helicity unsuppressed decay

$$R^\pi = \frac{\tau_{B^0}}{\tau_{B^-}} \frac{\mathcal{B}(B^- \to \tau^- \bar\nu)}{\mathcal{B}(\bar B^0 \to \pi^+ \ell^- \bar\nu)} = 0.73(13)$$ from here $\ell =$ avg. of $\mu + e$

[Fajfer, Kamenik, Nišandžić, Zupan, 1206.1872]

$R^\pi_{\mathsf{SM}} = 0.31(6)$ requires (improvable) decay constants and FFs from the lattice

I have nothing else to add about $B^- \to \tau^- \bar\nu$, will now focus on $b \to c\tau\bar\nu$ transitions

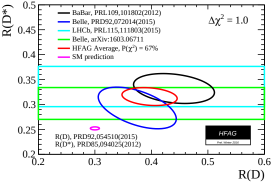
$B \to D^{(*)}\tau\bar{\nu}$
An $R(X)$ reminder

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

original goal: 2HDM $H^{\pm}$

- deviation first seen at BaBar, later results from Belle and LHCb
  BaBar/Belle full datasets $\tau \to \ell\nu\bar{\nu}$ to minimize lepton reco systematics

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle ($B_{\text{tag}}^{(\text{had})}$)	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
Belle ($B_{\text{tag}}^{(\ell)}$)		$0.302 \pm 0.030 \pm 0.011$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	$0.397 \pm 0.040 \pm 0.028$	$0.316 \pm 0.016 \pm 0.010$
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



  - clean SM observables: heavy quark symmetry relates FFs
    Caprini, Lellouch, Neubert, hep-ph/9712417
    cancellation of hadronic uncertainties, $|V_{cb}|$ in ratios
    lattice QCD for $R(D)$ only [MILC, 1503.07237; HPQCD, 1505.03925]
  - $R(D)$ — 1.9σ, $R(D^*)$ — 3.3σ
    total significance — 4.0σ largest deviation from SM right now!

- similar ratios before Belle II: LHCb: $R(D)$? $\Lambda_b \to \Lambda_c^{(*)}\tau\bar{\nu}$?
  BaBar/Belle: hadronic τ decays?

Evading unquantified systematics in SM calculations

Complementary theory predictions

- inclusive $B \to X_c \tau \bar{\nu}$ rate bounded by known exclusive modes
  [MF, Ligeti, Ruderman, 1506.08896]
  - form-factor independent OPE-based analysis – complementary theory systematics
  - Corrections up to $O(\Lambda_{\text{QCD}}/m_b, \alpha_s^2)$

$$R(X_c) = 0.223 \pm 0.004 \quad \text{theory}$$

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

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

(LEP: $\mathcal{B}(b \to X \tau^+ \nu) = (2.41 \pm 0.23)\%$)

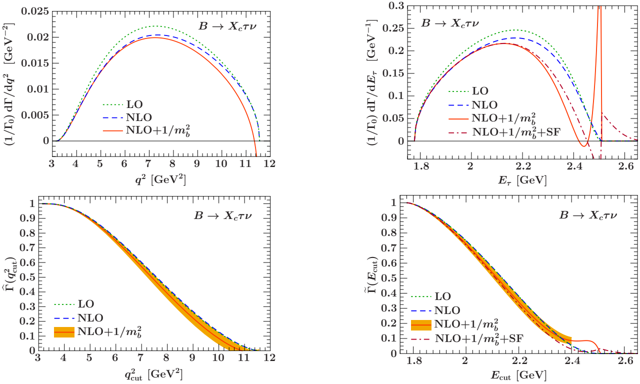
- isospin-constrained fit: $\mathcal{B}(\bar{B} \to D^* \tau \bar{\nu}) + \mathcal{B}(\bar{B} \to D \tau \bar{\nu}) = (2.78 \pm 0.25)\%$

- estimate rate to excited $\mathcal{B}(B \to D^{**} \tau \bar{\nu}) \gtrsim 0.2\%$
  get conservative limit: $\mathcal{B}(B \to D^{**} \ell \bar{\nu})/\mathcal{B}(B \to D^{(*)} \ell \bar{\nu}) \sim 0.3$

- deviation $\gtrsim 3\sigma$ in inclusive calculation (minimal non-perturbative inputs)
  - complementary to SM calculation of $R(D^{(*)})$ and LEP data

Leveraging inclusive spectra
Precision $d\Gamma(B \to X_c \tau \bar{\nu})/dq^2$ predictions

- no measurements since LEP,
  - papers in '90s used m_b^{pole}, no study of spectra (new data needed, in progress @ Belle)
  - large $1/m^2$ OPE corrections
- we've been told Belle analysis in progress



[Ligeti, Tackmann, 1406.7013]

leveraging inclusive spectra

All τ modes... $b \to u\tau\bar{\nu}$?

- if deviation clearly established, huge motivation to study all decay modes with τ
  - if LEP could measure $B \to X_c\tau\bar{\nu}$ with a few $\times\, 10^6$ B-$\bar{B}$ pairs ...
  - ... "surely" Belle II can measure $B \to X_u\tau\bar{\nu}$ with 5×10^{10} B-$\bar{B}$ pairs
- no inclusive distributions currently availible
  - $m_\tau \neq 0, m_u = 0$ – complications from different kinematic endpoints
  - 1.8 GeV $< E_\tau < 2.9$ GeV – Subtleties with shape function; match onto u jet?

[Ligeti, Luke, Tackmann, in progress]

- phase space suppression is smaller in $b \to u$:

$$\frac{\Gamma(B \to X_u\tau\bar{\nu})}{\Gamma(B \to X_u\ell\bar{\nu})} \simeq 0.333 \qquad \frac{\Gamma(B \to X_c\tau\bar{\nu})}{\Gamma(B \to X_c\ell\bar{\nu})} \simeq 0.222$$

- can LHCb/Belle II measure $b \to u\tau\bar{\nu}$ decay modes? ratios of τ/μ and/or c/u?
  - Other exclusive modes: $\Lambda_b \to \Lambda_{(c)}\tau\bar{\nu}$? $B \to \pi\tau\bar{\nu}$? $B \to \rho\tau\bar{\nu}$?

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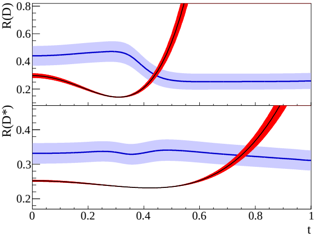
Redundant four-fermion operator analysis

- Fits to different fermion orderings convenient to understand allowed mediator

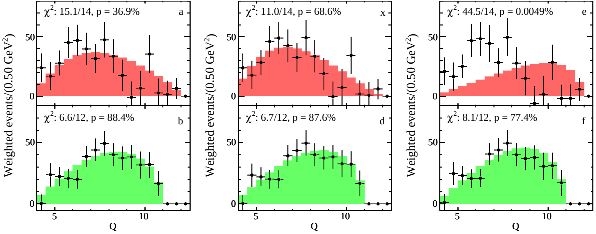
	Operator		Fierz identity	Allowed Current	$\delta\mathcal{L}_{\text{int}}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
$\mathcal{O}_{V_R}$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

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

BaBar q^2 spectral constraints



[1205.5442]

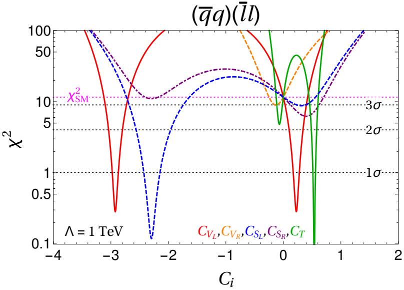


[1303.0571]

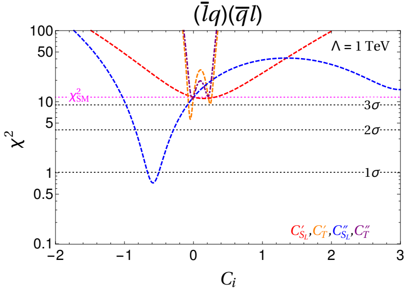
- BaBar studied q^2 spectrum of at D and D^* to observe consistency with 2HDM
  - type-II 2HDM and SM yield equally poor fits to data
  - other distributions can give sensitivity to, *e.g.*, D^*, τ polarization
  - non other disitrbutions publically availible
- no bin correlations released, we could only eyeball fits

Single operator fits

canonical 5 $\mathcal{O}$ operators



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



- All rates in the exact HQET limit

[W. Goldberger, hep-ph/9902311] (up to one overall typo)

Single operator fits

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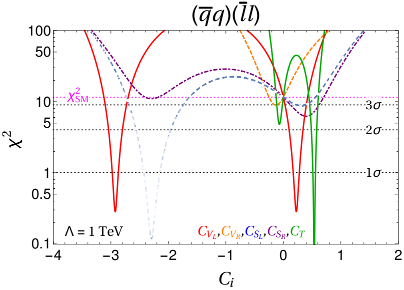

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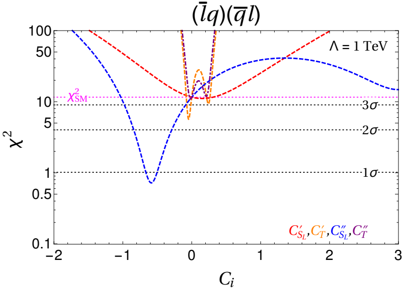

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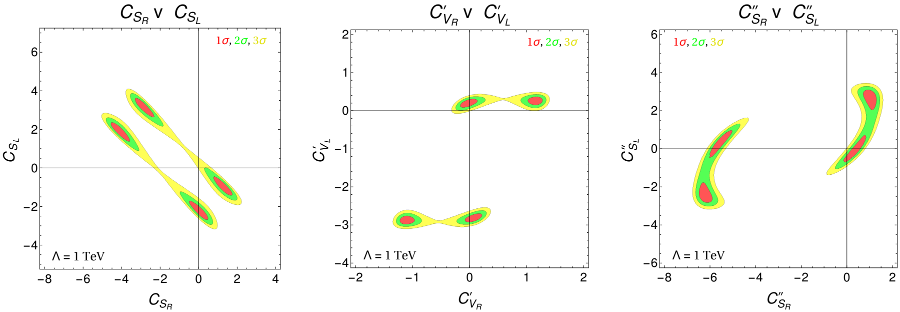
Two operator fits

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



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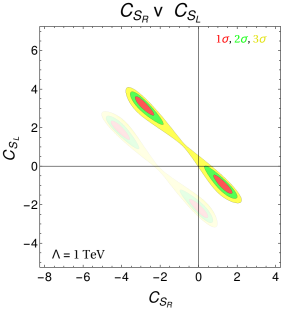
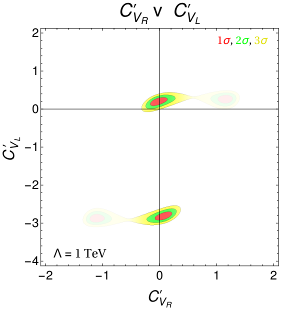
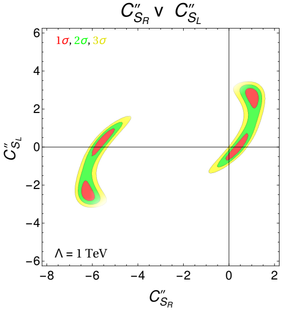


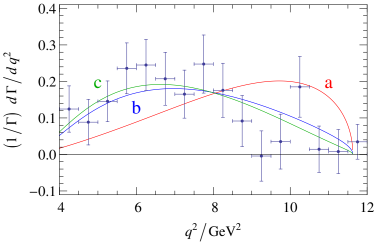




Operator coefficients

$C'_{V_L} = 0.24$	$C'_{V_R} = 1.10$
$C'_{V_L} = 0.24$	$C'_{V_R} = -0.01$
$C'_{V_L} = 0.96$	$C'_{V_R} = 2.41$

All q^2 constriaints come from $B \to D\tau\bar{\nu}$ rate



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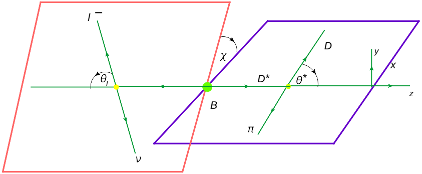
Differential observables
D^* *polarization*

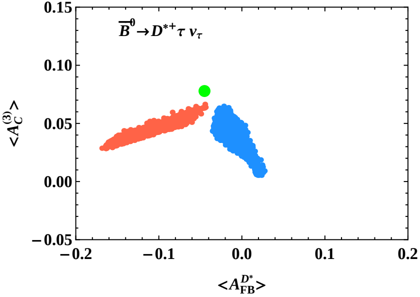
already saw q^2 spectrum constrain fits, what about other distributions?



[Duraisamy, Datta, 1302.7031]

correlations of D^* decay products and τ:

- D^* polarization fraction
- $A_F B$ lepton asymmetry
- transverse asymmetries
- CP-odd asymmetries



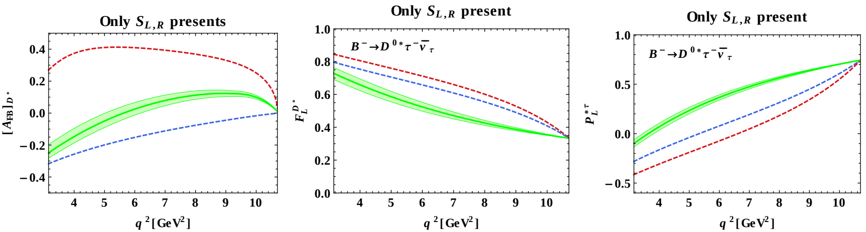
[Duraisamy, Sharma, Datta, 1405.3719]

distinguish op. fits with/without CP

analytic distribution recently computed in

[Alonso, Kobach, Camalich, 1602.07671]

Differential observables
τ polarization

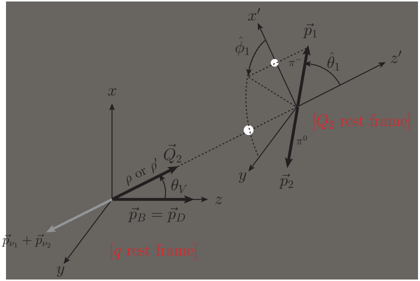


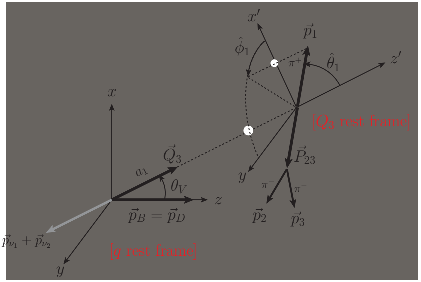
[Datta, Duraisamy, Ghosh, 1206.3760]

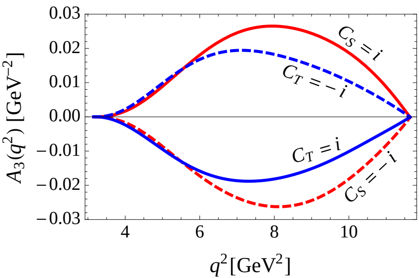
additional discrimination from considering τ polarization

Differential observables

CP observables in $B \to D\tau\bar{\nu}$







[Hagiwara, Nojiri, Sakaki, 1403.5892]

multi-prong hadronic τ decays allow for CP-sensitive observables in $B \to D\tau\bar{\nu}$ as well

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Some wilder ideas

Suppress, don't enhance

[MF, Ligeti, Ruderman, in progress]

- (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 at smaller Wilson coefficients comperable in both cases
- e and μ modes used for CKM matrix element extraction

$$V_{cb}^{(\text{exp})} \sim 0.9 V_{cb}^{(\text{SM})}, \quad V_{ub}^{(\text{exp})} \sim 0.9 V_{ub}^{(\text{SM})} \tag{1}$$

- 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 are in tension with such models
  - reduced tension with $R(D^{(*)})$ if CKM fits moved off central values — shifts to both within present uncertainties can lead to a self-consistent story
- current CKM limits on V_{ub} have killed BSM scenarios before, *e.g.* flavored GUTs
  - should some of these be revisited?

Some wilder ideas

$B \to D^{(*)} e\bar{\nu}$ vs. $B \to D^{(*)} \mu\bar{\nu}$

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

Parameters	De sample	$D\mu$ sample	combined result
ρ^2_D	$1.23 \pm 0.05 \pm 0.08$	$1.13 \pm 0.07 \pm 0.09$	$1.16 \pm 0.04 \pm 0.08$
ρ^2_{D*}	$1.23 \pm 0.02 \pm 0.07$	$1.24 \pm 0.03 \pm 0.07$	$1.33 \pm 0.04 \pm 0.09$
$\mathcal{B}(D^0 \ell\bar{\nu})(\%)$	$2.38 \pm 0.03 \pm 0.14$	$2.26 \pm 0.04 \pm 0.16$	$2.32 \pm 0.03 \pm 0.013$
$\mathcal{B}(D^{*0} \ell\bar{\nu})(\%)$	$5.45 \pm 0.03 \pm 0.22$	$5.27 \pm 0.04 \pm 0.37$	$5.48 \pm 0.04 \pm 0.02$
χ^2/n.d.f. (probability)	422/470 (0.94)	494/467 (0.19)	2.2/4 (0.71)

[BaBar, 0809.0828]

- Individual rates appear to be systematics limited
- We assumed e/μ universality, not a necessity
  - Reaching 1% level on ratio might be possible (but tough) even at Belle II
  - 10% e/μ non-universality still seems possible (despite what the PDG claims)
    — Simultaneous explaination of $\mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-)$ challenging

Signals both high and low (energy)

- LHC: (mostly) simple modifications of existing searches
  - extensions of $\tilde{t}/\tilde{b}$ searches to higher prod. cross sections
  - searches for $t\tau$ resonances, mixed $\bar{b}\tau\, t\bar{\nu}$ decay channels
  - $t \to b\tau\bar{\nu}$,$c\tau^+\tau^-$ non-resonant decays
  - on-shell t-channel states pp collisions
  - Enhanced $h \to \tau^+\tau^-$ rate (model dependent)
- Low energy probes:
  - more $B \to D^{(*)}\tau\bar{\nu}$ kinematic distributions, cross checks w/ inclusive deacys
  - look at ratios themselves differentially: $dR(D^{(*)})/dq^2$
  - Improve bounds on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$
  - $\mathcal{B}(D \to \pi\nu\bar{\nu}) \sim 10^{-5}$ possible (BES III?), enhanced $\mathcal{B}(D \to \mu^+\mu^-)$
  - $\mathcal{B}(B_s \to \tau^+\tau^-) \sim 10^{-3}$ possible

Conclusions

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  - complimentary, CKM-parameter-free families of ratio observables for LFU sensitivity
- Quantifying NP sensitivity
  - redundant effective operator bases for identification of UV physics
- NP descriminators
  - more differential distributions for discrimination of scenarios
- Consequences and Conclusions
  - no CKM or loop suppression in SM contribution
    $\Longrightarrow$ not how NP was "supposed to" show up
    maybe OK to think about some crazier ideas? (YMMV)
  - if it persists, robust ways of characterizing the excess exist
  - looking forward to more data

Thank you!