CKM2010 6th International Workshop on the CKM Unitarity Triangle

Theory of $B \to \ell \nu (\gamma)$ and $B \to D \tau \nu$

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8/9/2010, Warwick

Outline

- SM theory status
  - hadronic and parametric uncertainties
  - kinematically enhanced EM corrections
- Sensitivity to NP
  - Helicity suppressed charged currents, lepton flavor universality
  - CPV observables in $B \to D \ell \nu$

For Lattice QCD progress on f_B, $B \to D^{(*)}$ form factors determination
see talks by Nicolas Garron and Paul Mackenzie

SM theory of $B \to \ell\nu(\gamma)$

- Theoretical status of B → τν:

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

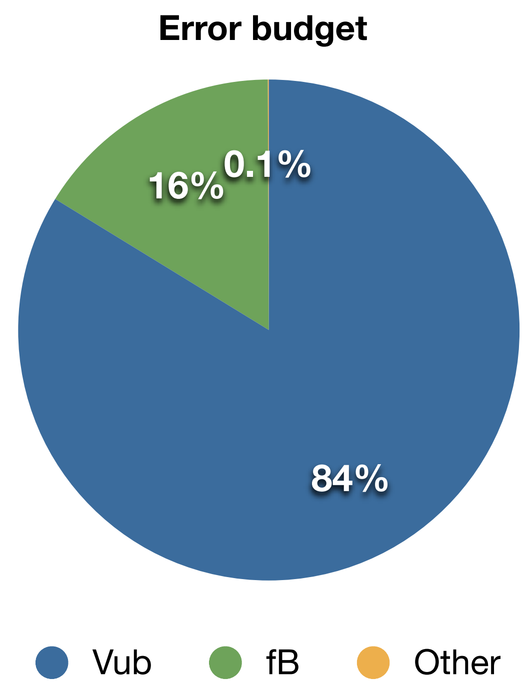
  - Main theoretical error due to f_B (~11% in Br) - Lattice QCD

    using Lattice average from J. Laiho, E. Lunghi & R. S. Van de Water, 0910.2928

  - Sizable parametric uncertainty in V_{ub} (~24% in Br)

    using CKMFitter average of exclusive and inclusive determinations from ICHEP'10

  - Other sources (τ_B, EM corrections) (~1% in Br)



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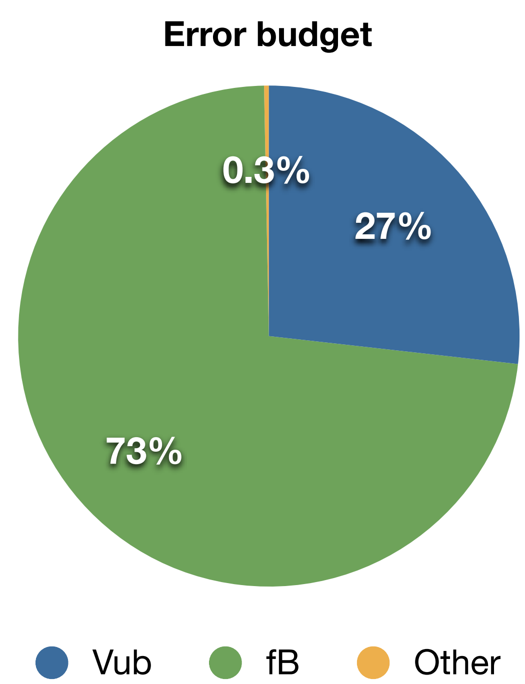
  - Sizable parametric uncertainty in V_{ub} (~6% in Br)
    using UTFit global fit (w/o B → τν) output 0908.3470
  - Other sources (τ_B, EM corrections) (~1% in Br)



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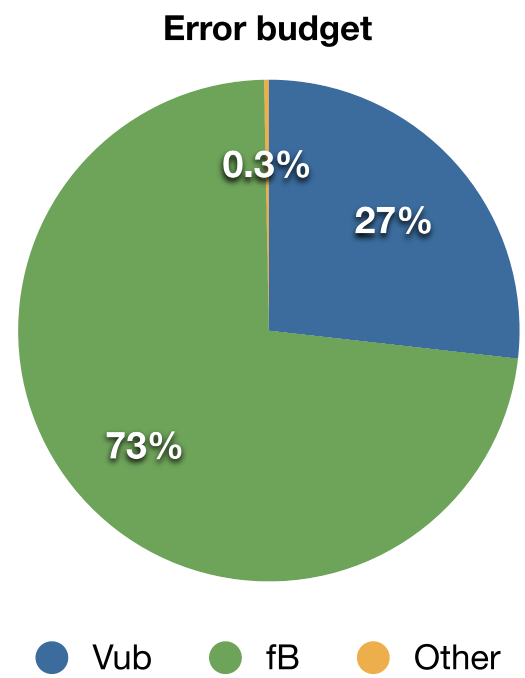

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  - Other sources (τ_B, EM corrections) (~1% in Br)
  - SM prediction: $\mathcal{B}(B^- \to \tau^- \bar{\nu})^{SM} = 1.13(1) \times 10^{-4} \left(\frac{f_B}{0.2\text{GeV}}\right)^2 \left(\frac{|V_{ub}|}{4 \times 10^{-3}}\right)^2$

$$\left[\frac{\Gamma(B \to \mu\nu)}{\Gamma(B \to \tau\nu)}\right]^{SM} = 4.49 \times 10^{-3\star} \quad \left[\frac{\Gamma(B \to e\nu)}{\Gamma(B \to \tau\nu)}\right]^{SM} = 1.05 \times 10^{-7\star}$$

*w/o EM corrections

SM theory of $B \to \ell\nu(\gamma)$

- Main uncertainties are reducible using ΔM_{Bd} and UT angles

$$\left.\frac{B(B^- \to \tau^- \bar{\nu})}{\tau_B \Delta M_{B_d}}\right|^{\rm SM} = \frac{3\pi}{4\eta_B S_0(m_t^2/M_W^2)\hat{B}_{B_d}} \frac{m_\tau^2}{M_W^2}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 \left|\frac{V_{ub}}{V_{td}}\right|^2$$

K. Ikado, FPCP 2006
G. Isidori and P. Paradisi, hep-ph/0605012

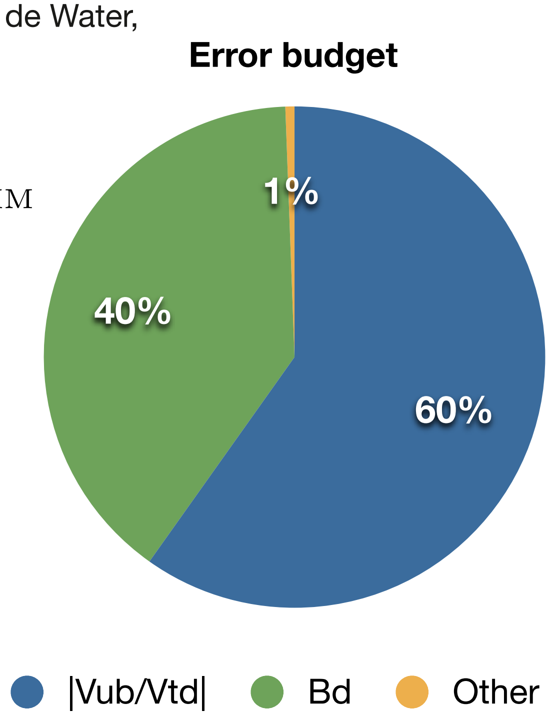
- Reduced hadronic sensitivity in B_{Bd} (9%) using Lattice average from J. Laiho, E. Lunghi & R. S. Van de Water, 0910.2928

- Modified parametric uncertainty in $|V_{ub}/V_{td}| = |\sin\beta_{\rm CKM}/\sin\gamma_{\rm CKM}$ (~11% in Br) using UTFit global fit (w/o B → τν) output 0908.3470

- Additional uncertainties due to m_t, ΔM_{Bd} (~1% in Br)

- SM prediction:

$$\mathcal{B}(B^- \to \tau^- \bar{\nu})^{SM} = 0.94(1) \times 10^{-4} \left(\frac{1}{B_{B_d}(m_b)}\right)\left(\frac{2}{|V_{td}/V_{ub}|}\right)^2$$



SM theory of $B \to \ell\nu(\gamma)$

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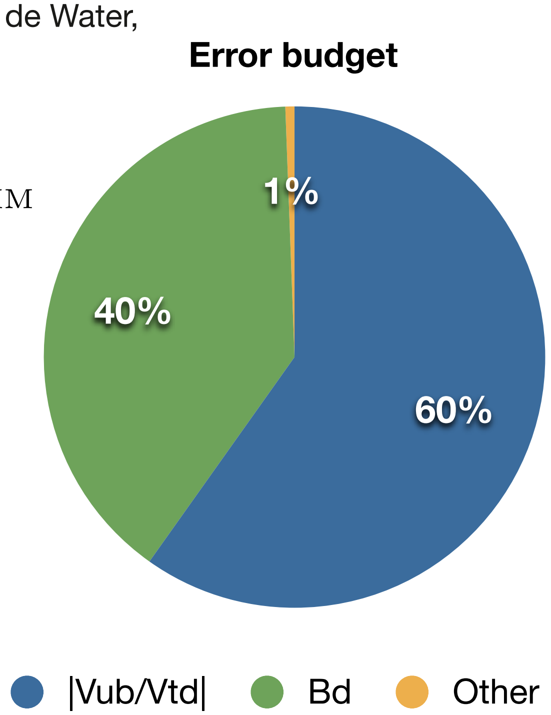

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CKMfitter, 0905.1572

UTfit 0908.3470

Soni & Lunghi 0912.0002

Recently explored to point out tensions in UT fit

see tuesday's talk by Paride Paradisi

SM theory of $B \to \ell\nu(\gamma)$

- Emission of additional photon can lift helicity suppression
  - Inner bremsstrahlung (IB) photons originating from point-like sources
    - can be computed exactly (Low's theorem), still helicity suppressed
  - Structure dependent (SD) contributions
    - lift helicity suppression

J. Bijnens et al., hep-ph/9209261

G. Burdman et al., hep-ph/9405425

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha G_F^2}{48\pi^2}|V_{ub}|^2 m_B^4 \left(f_A^2(E_\gamma) + f_V^2(E_\gamma)\right) x(1-x)^3 \qquad x = \frac{2E_\gamma}{m_B}$$

    - need to compute matrix element $\langle\gamma|\bar{b}\gamma_\mu(1-\gamma_5)u|B\rangle$

D. Bećirević et al., 0907.1845

      - f_A, f_V form factors resonantly enhanced due to low lying B*

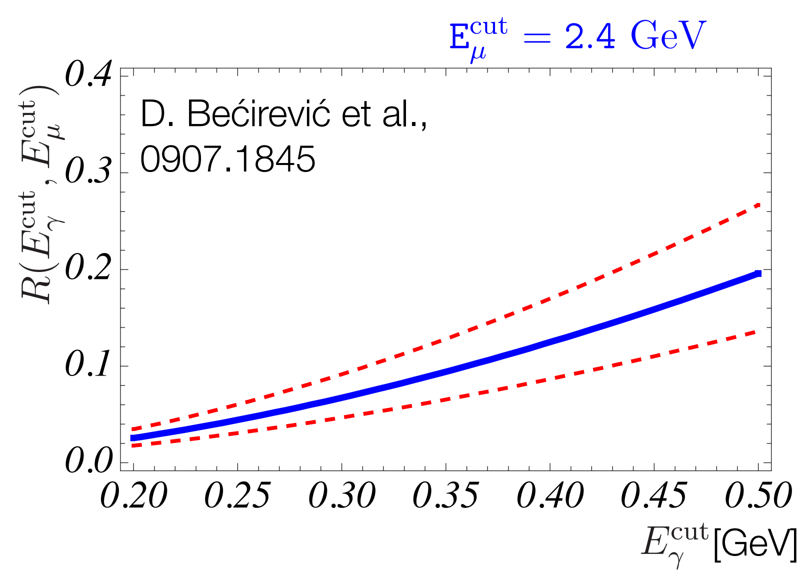
SM theory of $B \to \ell\nu(\gamma)$

- Experiments impose finite cuts on final state photon and lepton energies

$$R(E_\gamma^{\rm cut}, E_\mu^{\rm cut}) \;=\; \frac{\Gamma^{SD}(B \to \mu\nu\gamma; E_\gamma < E_\gamma^{\rm cut}; E_\mu > E_\mu^{\rm cut})}{\Gamma(B \to \mu\nu)}$$

  - In present setups SD effects below 1% in $B \to \tau\nu(\gamma)$
  - Up to 20% in $B \to \mu\nu(\gamma)$
  - Limits the reach for $B \to e\,\nu$

  (Also relevant for charm decays)



- IB contributions become relevant for $E_\gamma^{\rm cut}$<<100MeV & $E_\mu^{\rm cut}$>2.6GeV

- SD contributions ~lepton flavor universal, can be experimentally subtracted

  $\Gamma(B \to \mu\nu(\gamma)) - \Gamma(B \to e\nu(\gamma))$ free of SD contributions, can determine $B \to \mu\nu$

SM theory of $B \to D^{(*)} \ell \nu$

- Main theoretical uncertainties due to form factors - Lattice QCD ($w=v_B \cdot v_D$)

$$\frac{d\Gamma(B \to D\ell\nu)}{dw} = \frac{G_F^2}{48\pi^3} m_D^3 (m_B + m_D)^2 (w^2-1)^{3/2} |V_{cb}|^2 |\mathcal{G}(w)|^2,$$

$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw} = \frac{G_F^2}{4\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 \sqrt{w^2-1} |V_{cb}|^2 \chi(w) |\mathcal{F}(w)|^2,$$

  - at w=1 HQ symmetry predicts G(1)= F(1) =1 - susceptible to α_s and $1/m_Q$ corrections (can be large)

$$\mathcal{G}(1) = 1 + c_V(\alpha_s) + \frac{c_{\text{nonp.}}}{m_Q}$$

$$\mathcal{F}(1) = 1 + c_A(\alpha_s) + \frac{c^*_{\text{nonp.}}}{m_Q^2}$$

A. Czarnecki, hep-ph/9603261
Czarnecki & Melnikov, hep-ph/9703277

Z. Ligeti et al., hep-ph/9305304
M. Neubert, Phys. Rev. D 46, 2212.

  - compute $1/m_Q$ terms on Lattice - calculate residual perturbative corrections from matching

J. Harada et al., hep-lat/0112044
S. Hashimoto et al., hep-ph/0110253
S. Hashimoto et al., hep-ph/9906376

See talk by Paul Mackenzie

SM theory of $B \to D^{(*)} \ell \nu$

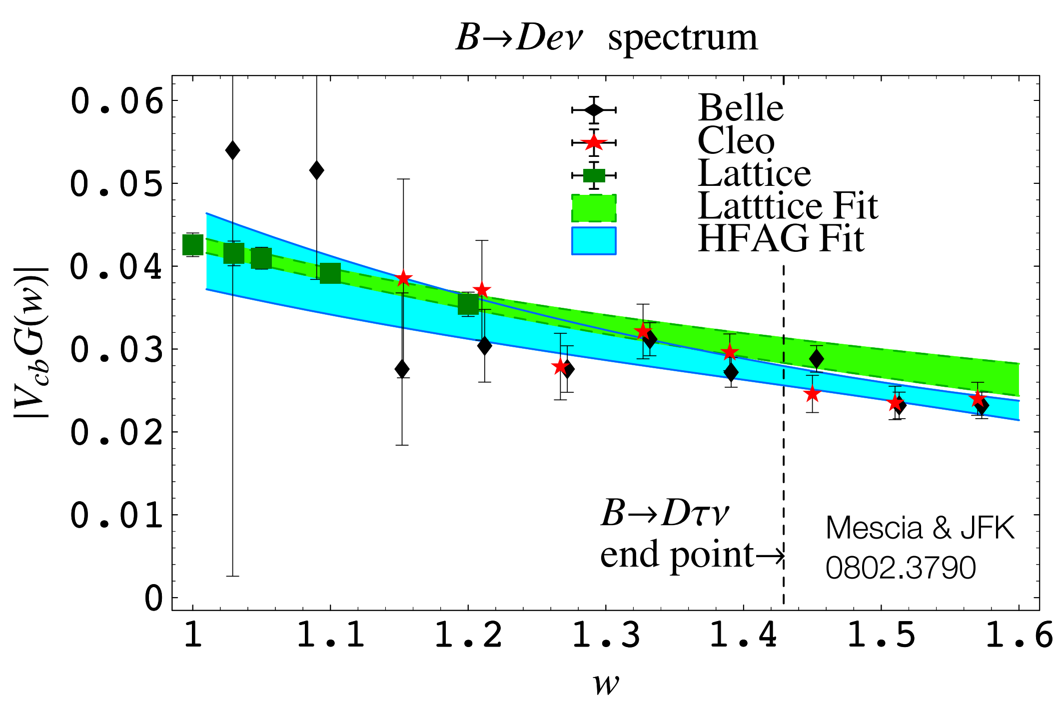
- In order to compare to experiment need to extrapolate away from zero recoil
  - 1-parameter extrapolation using analyticity, unitarity & HQ symmetry

$$\mathcal{G}(w) = \mathcal{G}(1)\left[1 - 8\rho_D^2 z + (51\rho_D^2 - 10)z^2 - (252\rho_D^2 - 84)z^3\right],$$

I. Caprini, et al.
hep-ph/9712417

Similar for F(w)

  - More robust: Lattice can compute FFs away from endpoint
  - Can be cross-checked with experimentally measured distributions



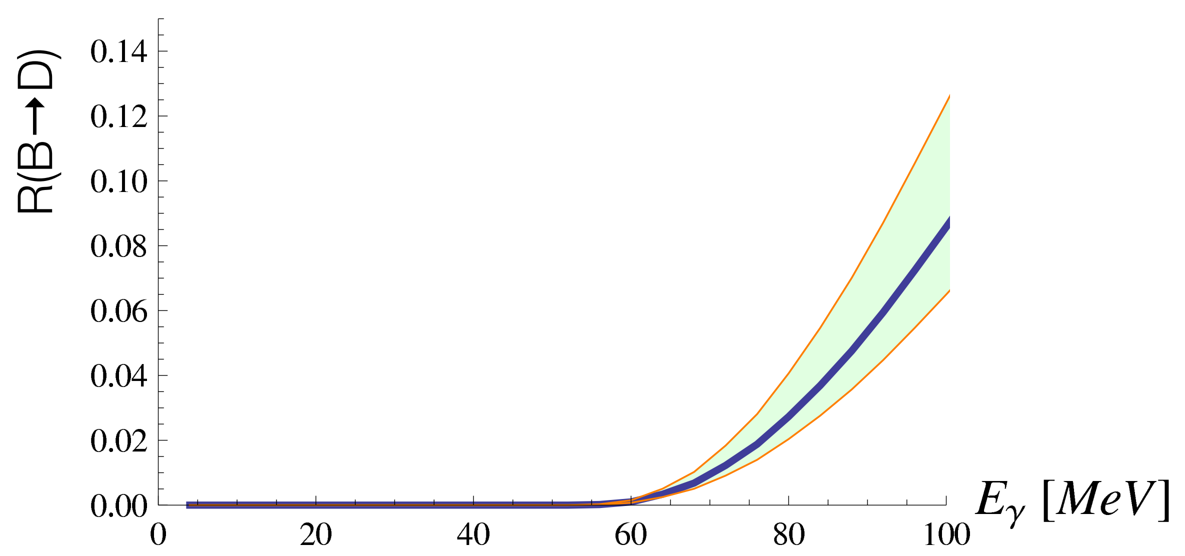
SM theory of $B \to D^{(*)} \ell \nu (\gamma)$

- QED corrections at partonic level known (0.7%) — A. Sirlin, Nucl. Phys. B196 (1982) 83.

- IB soft photons under control

- SD terms can be resonantly enhanced in $B \to D \ell \nu$ due to the nearby D^*

  Bećirević & Košnik, 0910.5031



  - can affect extraction of V_{cb} $B \to D \ell \nu$

SM theory of $B \to D^{(*)}\tau\nu$

- Presence of massive tau lepton introduces sensitivity to an additional FF
  - Deviations from HQ limit can be computed on the Lattice

    N. Tantalo, 0710.0729
    G. M. de Divitiis et al., 0707.0587, 0707.0582

  - Or estimated using perturbative corrections & HQE

    Nierste et al., 0801.4938
    Tanaka & Watanabe, 1005.4306

- Most other theory & parametric uncertainties cancel in the ratio

$$R \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)}$$

$$R^{SM} = 0.302(15)$$ Tanaka & Watanabe, 1005.4306

$$= 0.296(16)$$ update of Mescia & JFK 0802.3790 using Lattice estimates

New physics in $B \to \ell\nu(\gamma)$

- Mediated by helicity suppressed charged currents - sensitive to extended scalar sectors

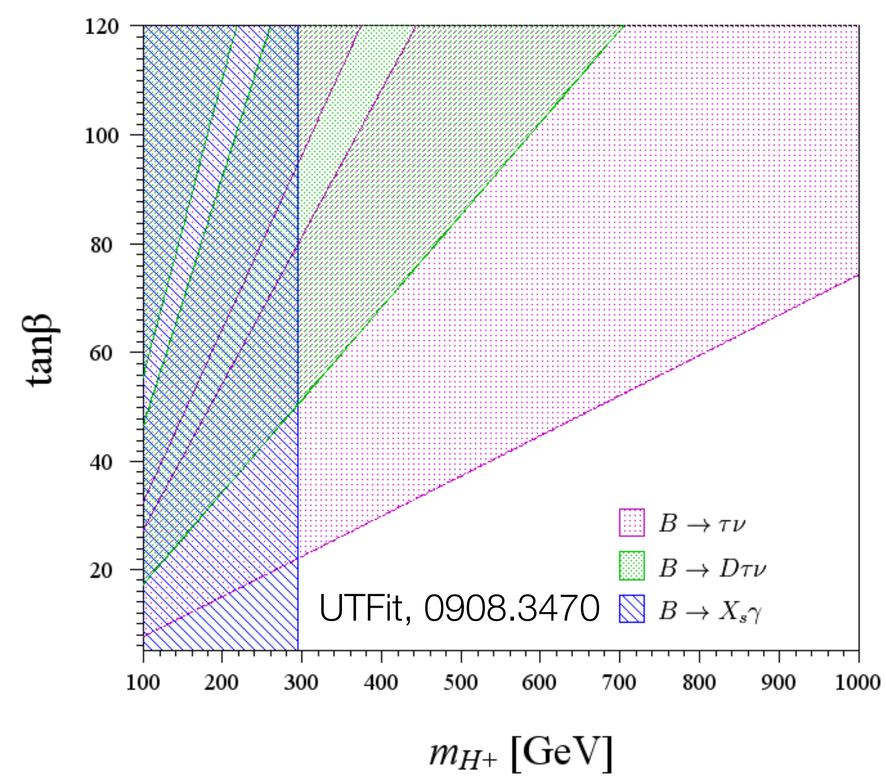
Hou, W.-S., 1993, Phys. Rev. D48, 2342.

$$\mathcal{H}_{eff}^{b\to q} = \frac{G_F}{\sqrt{2}} V_{qb} \sum_{\ell=e,\mu,\tau} \Big[(\bar{q}\gamma_\mu(1-\gamma_5)b)\,(\bar{\ell}\gamma^\mu(1-\gamma_5)\nu) + C_{NP}^{\ell}(\bar{q}(1+\gamma_5)b)\,(\bar{\ell}(1-\gamma_5)\nu_\ell) \Big] + \text{h.c.}\,.$$

$$\frac{\mathcal{B}(B\to\tau\nu)}{\mathcal{B}(B\to\tau\nu)^{SM}} = \left| 1 + \frac{m_B^2}{m_b m_\tau} C_{NP}^{\tau} \right|^2$$

- Example THDMII (MFV MSSM)

$$C_{NP}^{\ell} \quad = \quad -\frac{m_b m_\ell}{m_{H^+}^2} \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta}$$



New physics in $B \to \ell\nu(\gamma)$

- LFV can also contribute to lepton flavor universality ratios

M.Ciuchini, et al., hep- ph/9806308

$$R_P^{\ell_1/\ell_2} = \frac{B(P \to \ell_1\nu)}{B(P \to \ell_2\nu)}$$

- Within the MSSM large values of tanβ and sizable mixing angles in the right-slepton sector still allowed

A. Masiero et al., hep-ph/0511289, 0807.4721
J. Ellis et al., 0809.5211

  - can only enhance electron mode

- Also analyzed in a MLFV effective theory approach

Filipuzzi & Isidori, 0906.3024

  - effects correlated with LFV (μ-e nuclear conversion)
  - 50% effects in $R_B^{\mu/\tau}$ still allowed

New physics in $B \to \ell\nu(\gamma)$

- Relevant for consistency check of V_{ub} extraction
  - Example: presence of right-handed currents will affect it differently than $B \to \pi \ell \nu$ or $B \to X_u \ell \nu$

$$\mathcal{L}_{\rm eff}^{c.c.} = -\frac{4G_F}{\sqrt{2}}\ \bar{u}\gamma^\mu \left[(1+\epsilon_L)VP_L + \epsilon_R \widetilde{V} P_R\right] d\ (\bar{\ell}_L \gamma_\mu \nu_L)\ +\ \text{h.c.}$$

$$\left(|V_{ub}|^{\rm incl}_{\rm SM\text{-}exp}\right)^2 = \left(|V_{ub}|^2 + |\epsilon_R|^2 |\widetilde{V}_{ub}|^2\right)$$

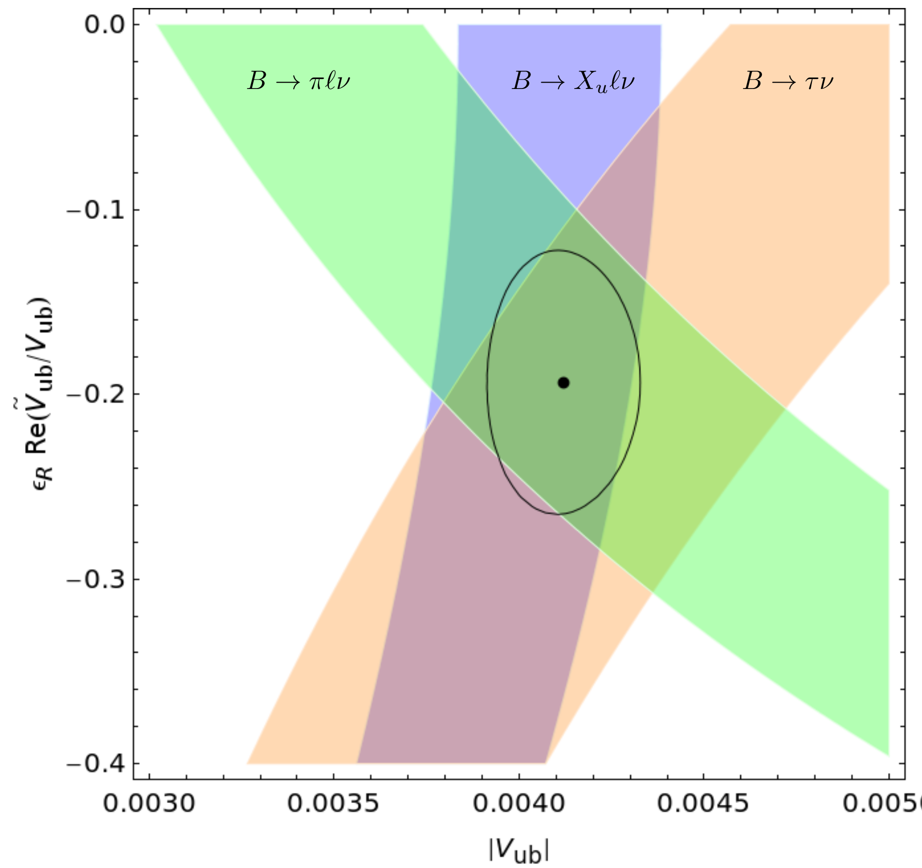
$$|V_{ub}|^{B\to\pi}_{\rm SM\text{-}exp} = |V_{ub} + \epsilon_R \widetilde{V}_{ub}|$$

$$|V_{ub}|^{B\to\tau}_{\rm SM\text{-}exp} = |V_{ub} - \epsilon_R \widetilde{V}_{ub}|$$

  - Can remove tensions among different V_{ub} determinations

(Similar tensions in Vcb extraction cannot be explained in this way)

A. J. Buras et al., 1007.1993
R. Feger et al., 1003.4022
A. Crivellin 0907.2461



New physics in B→D$^{(*)}$τν

- Helicity suppressed contribution sensitive to extended scalar sectors

$$\frac{d\Gamma(B\to D\tau\nu)}{dw} = \frac{d\Gamma(B\to D\ell\nu)}{dw}\left[1-\frac{m_\tau^2}{m_B^2}\left|1+\frac{t(w)}{(m_b-m_c)m_\tau}C_{NP}^\tau\right|^2 \mathcal{S}(w,m_\tau)\right]$$

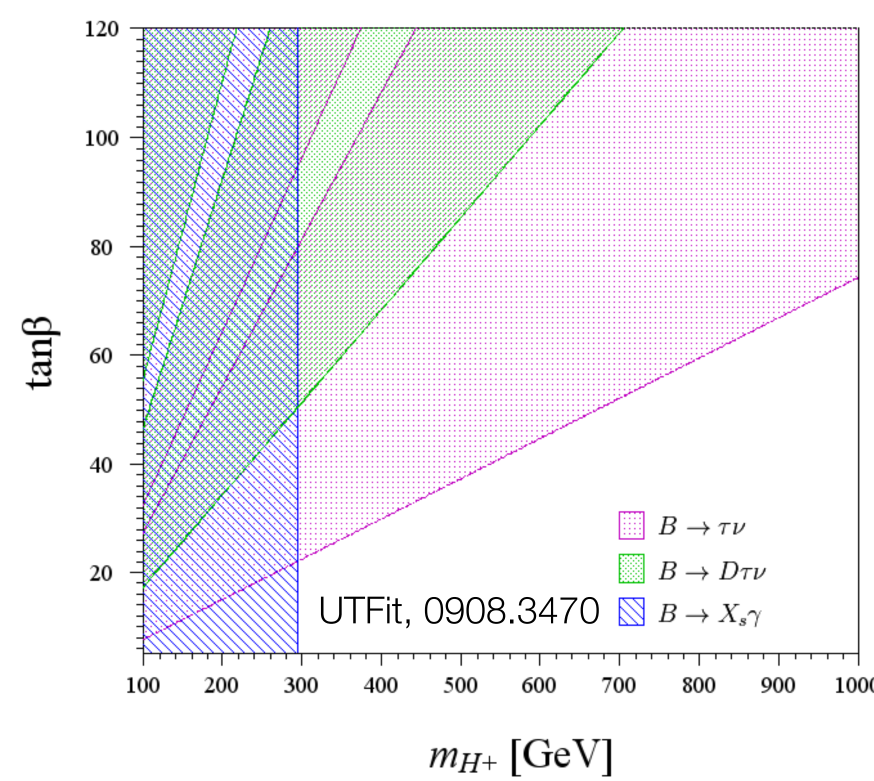
Kiers & Soni, hep-ph/9706337
Chen & Geng, JHEP 10, 053.
M. Tanaka, Z. Phys. C67, 321.

- Modification of the ratio of tau and light lepton rates

$$R/R^{SM} \quad = \quad 1+1.5(1)Re(C_{NP}^\tau)+1.1(1)|C_{NP}^\tau|^2$$

update of
J.F.K. & F. Mescia
0802.3790

- Complementary constraint on THDMII



New physics in $B \to D^{(*)} \tau \nu$

- Additional kinematical and lepton spin observables allow access to NP phases
  - transverse lepton polarization

Grossman & Ligeti, Phys. Lett. B347, 399.
D. Atwood et al., Phys. Rev. Lett. 71, 492.
R. Garisto, Phys. Rev. D51, 1107.

$$p_\tau^T \equiv \vec{S}_\tau \cdot \vec{p}_\tau \times \vec{p}_X / |\vec{p}_\tau \times \vec{p}_X|$$

  - vanishes in the SM
  - sensitive to the presence of a CP-odd phase in scalar interactions
    suited as a probe of CP violating multi-Higgs doublet models

Probe helicity suppressed sources of CPV

New physics in B→D$^{(*)}$τν

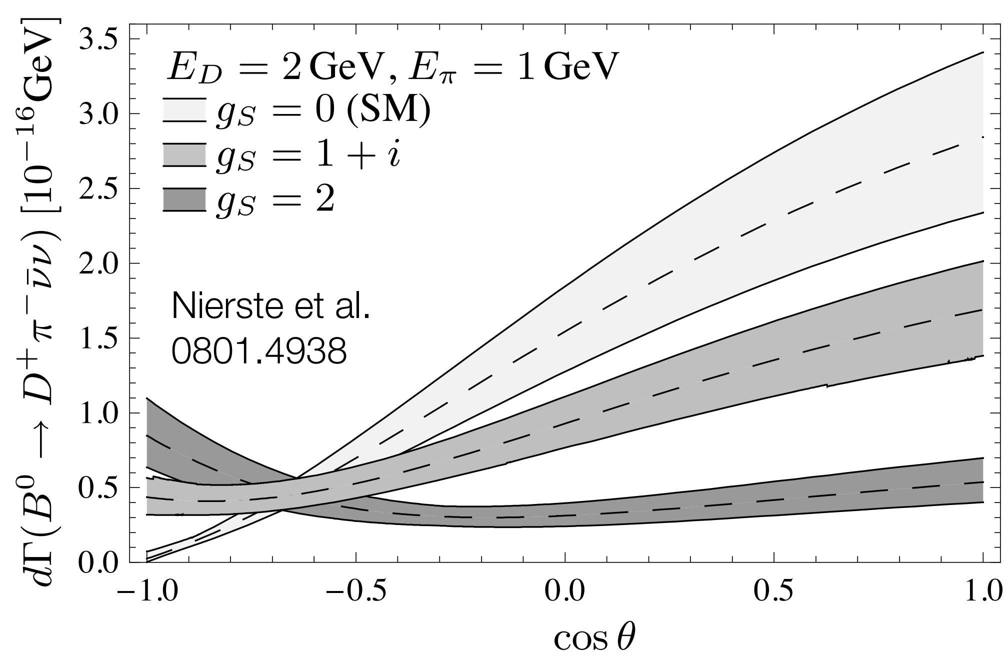
- Additional kinematical and lepton spin observables allow access to NP phases
  - Self analyzing virtue of tau - one can look at pion angle distribution in its two-body hadronic decay mode in $\bar{B} \to D\bar{\nu}_\tau\tau^-[\to \pi^-\nu_\tau]$
    - Example: angle between D and π in B rest frame

Grzadkowski, & Hou, Phys. Lett. B283, 427

T. Miki et al., hep-ph/0210051

Nierste et al. 0801.4938

Tanaka & Watanabe 1005.4306



discriminates between CPV phase of charged Higgs contribution

Summary

- $B \to \ell\nu$ and $B \to D\,\tau\nu$ are probes of helicity suppressed charged currents
    - SM precision of $B \to \tau\nu$ dominated by parametric uncertainties and/or f_B

      Predictions based on inputs from global fits with tensions should be interpreted carefully

    - Precise determination of $B \to \mu\nu(\gamma)$ requires careful treatment of kinematically enhanced SD EM corrections

    - In SM $B \to D\,\tau\nu$ rates normalized to $B \to D\,\ell\nu$ modes are known precisely

      5% uncertainty dominated by estimates of the scalar form factor

Summary

- $B \to \ell\nu$ and $B \to D\,\tau\nu$ are probes of helicity suppressed charged currents
  - extended scalar sectors will affect both observables - complementarity
  - flavor universality ratio $R_B^{\mu/\tau}$ can receive sizable LFV NP contributions
  - important modes for cross-checking V_{ub} and V_{cb} determinations
  - tau spin polarization in $B \to D\,\tau\nu$ provides experimental access to helicity suppressed new sources of CPV