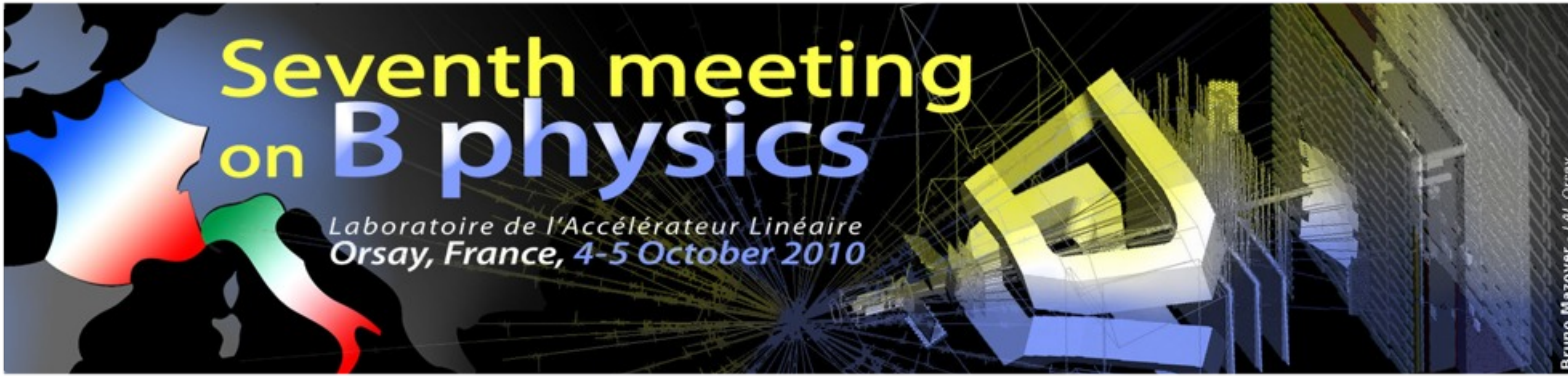


New physics in rare B decays : a theoretical view

Jernej F. Kamenik

Institut "Jožef Stefan"

4/10/2010, Orsay

Outline

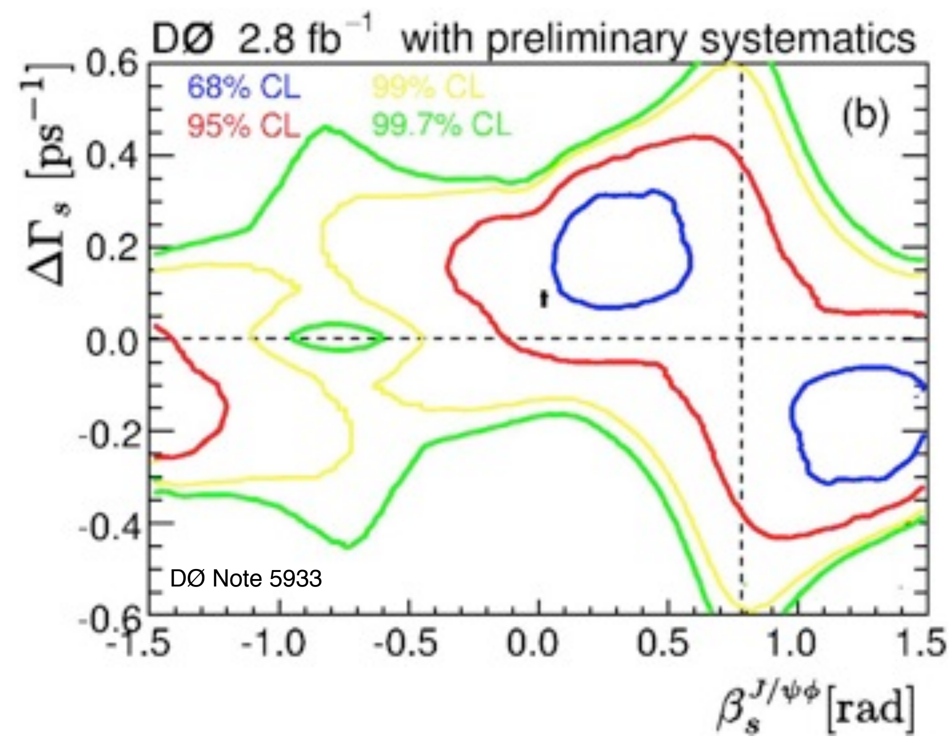
- CPV in the B and B_s systems: First hints of new (flavor) CPV physics?
- Implications for rare $\Delta B=1$ FCNC and helicity suppressed processes
- Probing the unexpected with rare $B \to K^{(*)} E_{miss}$ decays

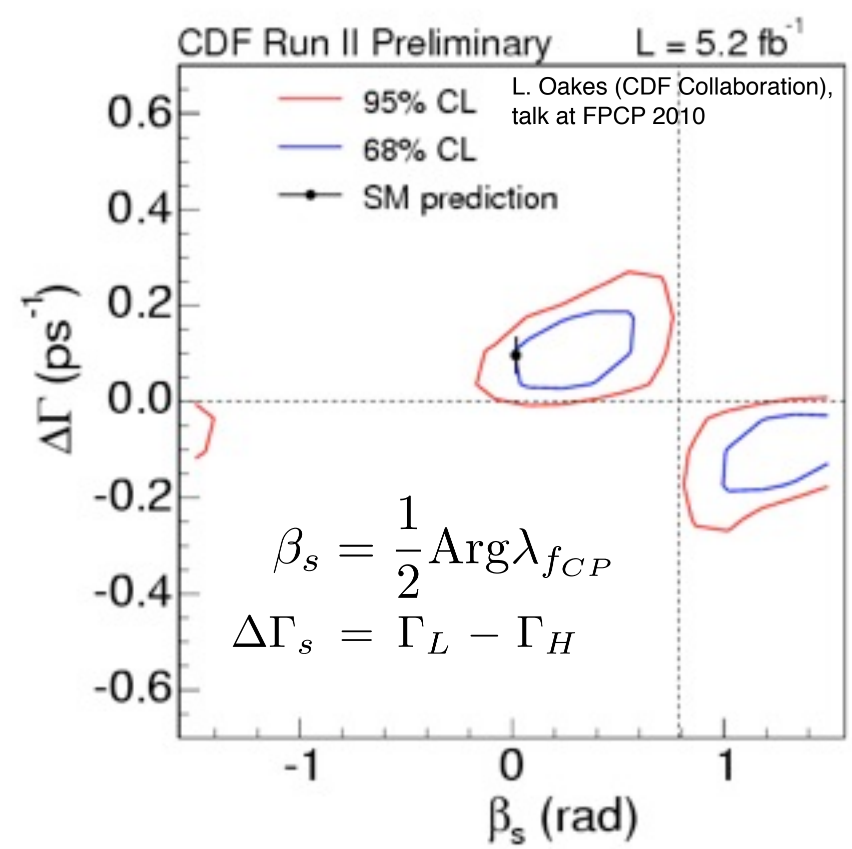
Recent developments in the B_s system

- During the last three years increasing experimental hints of sizable CPV in B_s sector

Recent developments in the B_s system

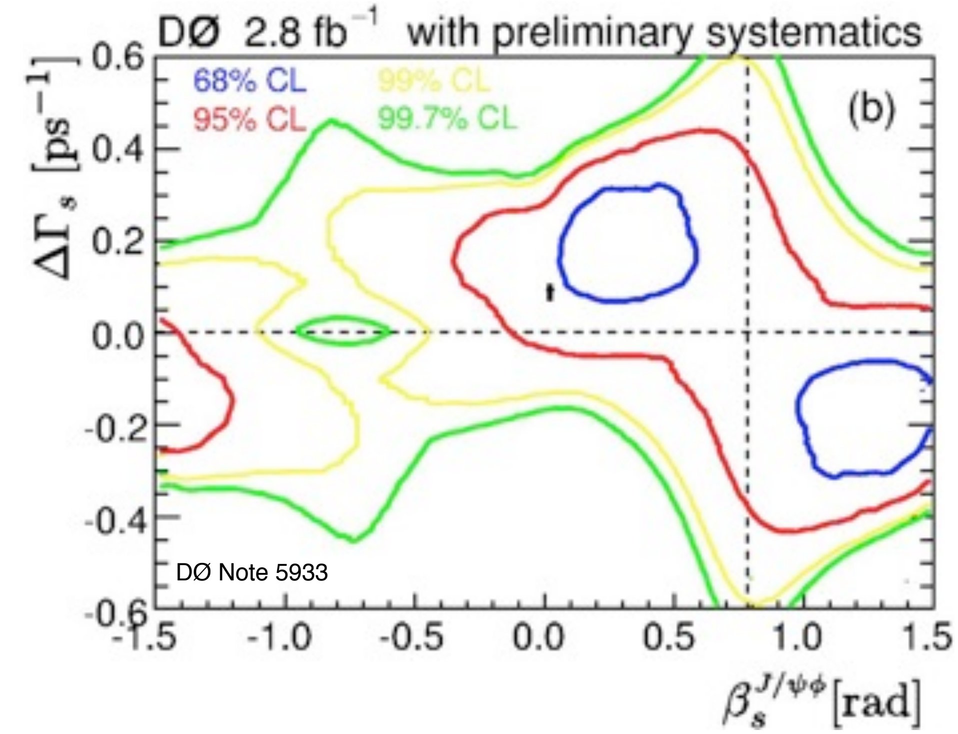
- During the last three years increasing experimental hints of sizable CPV in B_s sector
    - Hints of large (mixing-induced) CP Violation in $B_s \to J/\psi\ \phi$ decays





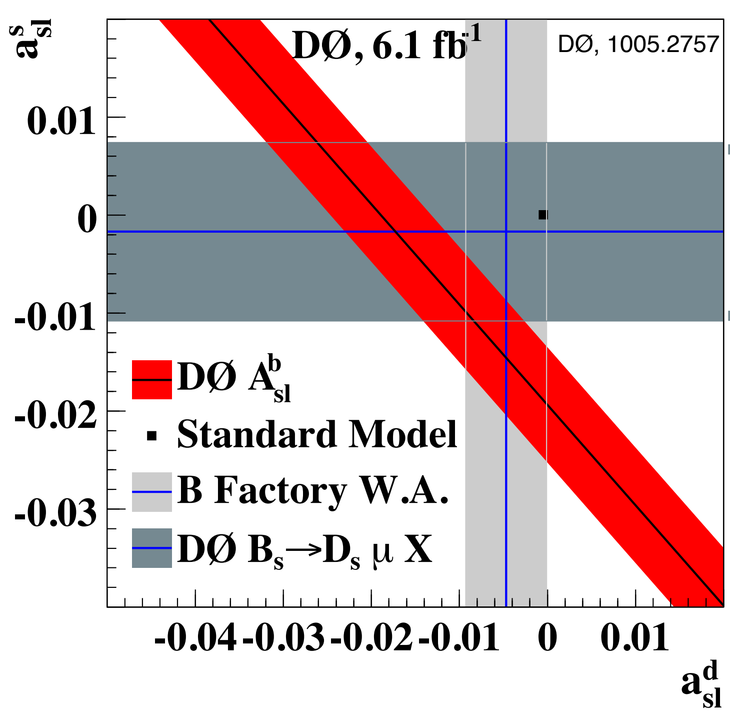
Recent developments in the B_s system

- During the last three years increasing experimental hints of sizable CPV in B_s sector
    - Hints of large (mixing-induced) CP Violation in $B_s \to J/\psi\, \phi$ decays
    - Evidence for an anomalous like-sign dimuon charge asymmetry (b-inclusive)

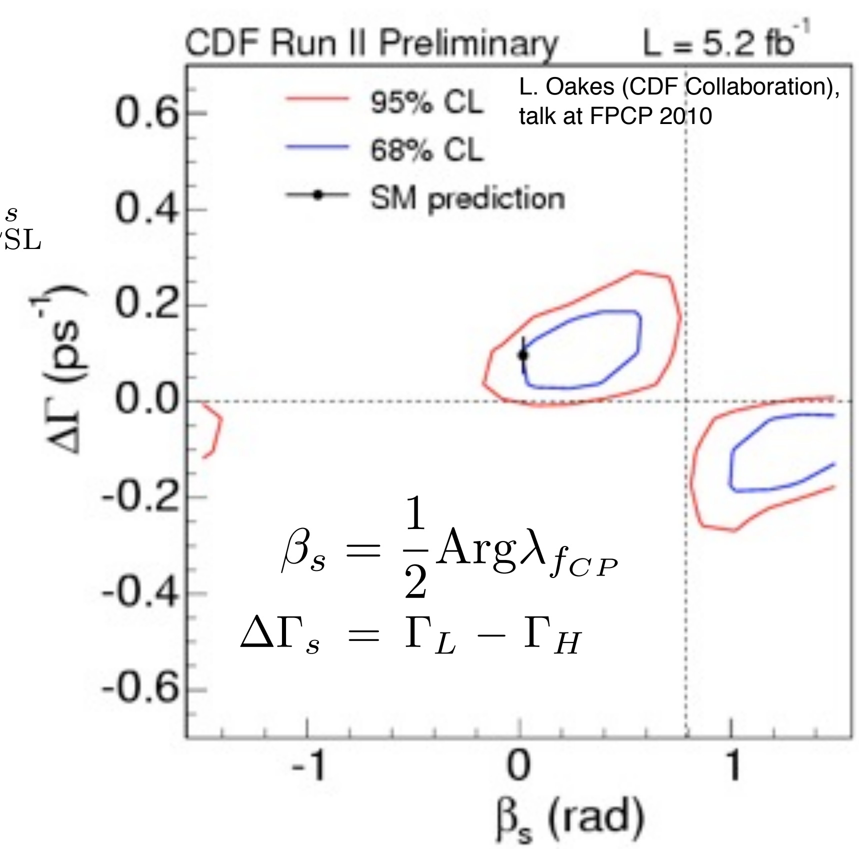


$$a^b_{\rm SL} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \quad b\bar{b} \to \mu^+\mu^+ X$$

$$a^b_{\rm SL} = (0.506 \pm 0.043)\, a^d_{\rm SL} + (0.494 \pm 0.043)\, a^s_{\rm SL}$$



Assumes no CPV
in relevant tree decays
[DØ, 0904.3907]



Recent developments in the B_S system

- Theoretical interpretation
  - In the SM all CPV B_s observables precisely predicted in terms of an angle in the squashed CKM UT $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = (1.04 \pm 0.05)^\circ$

a^b_{SL} @ 3.2σ   [β_s, ΔΓ] @ 44% C.L. (CDF),   24% C.L. (DØ)

Recent developments in the B_s system

- Theoretical interpretation
  - In the SM all CPV B_s observables precisely predicted in terms of an angle in the squashed CKM UT $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = (1.04 \pm 0.05)^\circ$

    a^b_{SL} @ 3.2σ [β_s, ΔΓ] @ 44% C.L. (CDF), 24% C.L. (DØ)

  - CPV NP could in principle contribute either in mixing or in decays
    - In decays would need to compete against tree-level SM contributions

      see however Dighe et al. 1005.4051
    - New effects in mixing predict correlations between observables

Recent developments in the B_s system

- Theoretical interpretation
  - In the SM all CPV B_s observables precisely predicted in terms of an angle in the squashed CKM UT $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = (1.04 \pm 0.05)^\circ$

    a^b_{SL} @ 3.2σ [β_s, ΔΓ] @ 44% C.L. (CDF), 24% C.L. (DØ)

  - CPV NP could in principle contribute either in mixing or in decays
    - In decays would need to compete against tree-level SM contributions

      see however Dighe et al. 1005.4051
    - New effects in mixing predict correlations between observables

Can be tested!

Recent developments in the B_s system

- Theoretical interpretation: *NP in B_s mixing hypothesis*
  - If no CPV in decays, consistency relation between observables

Grossman, Nir, Perez, 0904.0305

$$a^s_{\rm SL} = -\frac{|\Delta\Gamma_s|}{\Delta m_s}\, S_{\psi\phi} \,/\, \sqrt{1 - S^2_{\psi\phi}} \qquad (S_{\psi\phi} = \sin 2\beta_s^{\rm eff})$$

✔ Satisfied by current measurements

Recent developments in the B_s system

- Theoretical interpretation: *NP in B_s mixing hypothesis*
  - If no CPV in decays, consistency relation between observables

Grossman, Nir, Perez, 0904.0305

$$a_{\rm SL}^s = -\frac{|\Delta\Gamma_s|}{\Delta m_s}\, S_{\psi\phi} \,/\, \sqrt{1 - S_{\psi\phi}^2} \qquad (S_{\psi\phi} = \sin 2\beta_s^{\rm eff})$$

✔ Satisfied by current measurements

  - Inclusive dimuon asymmetry sensitive to NP in both B and B_s mixing

Ligeti et al. 1006.0432

    - Parameterize NP:

$$\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM} \left|1 + h_q e^{2i\sigma_q}\right| , \\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM} \cos\left[\arg\left(1 + h_s e^{2i\sigma_s}\right)\right] , \\
A_{\rm SL}^q &= {\rm Im}\left\{\Gamma_{12}^q / \left[M_{12}^{q,{\rm SM}} (1 + h_q e^{2i\sigma_q})\right]\right\} , \\
S_{\psi K} &= \sin\left[2\beta + \arg\left(1 + h_d e^{2i\sigma_d}\right)\right] , \\
S_{\psi\phi} &= \sin\left[2\beta_s - \arg\left(1 + h_s e^{2i\sigma_s}\right)\right] .
\end{aligned}$$

Recent developments in the B_s system

- Theoretical interpretation: *NP in B_s mixing hypothesis*
  - If no CPV in decays, consistency relation between observables

Grossman, Nir, Perez, 0904.0305

$$a^s_{\rm SL} = -\frac{|\Delta\Gamma_s|}{\Delta m_s}\, S_{\psi\phi} \,/\sqrt{1 - S^2_{\psi\phi}} \qquad (S_{\psi\phi} = \sin 2\beta_s^{\rm eff})$$

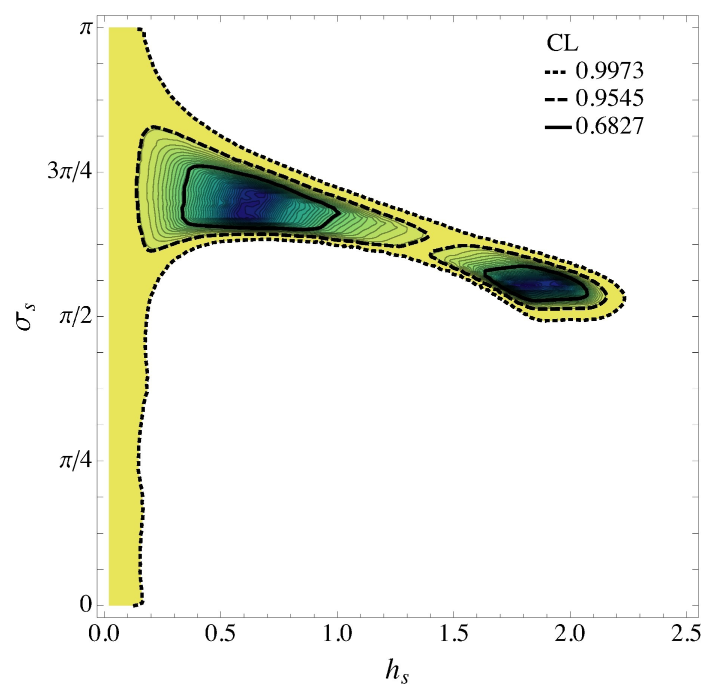
✔ Satisfied by current measurements

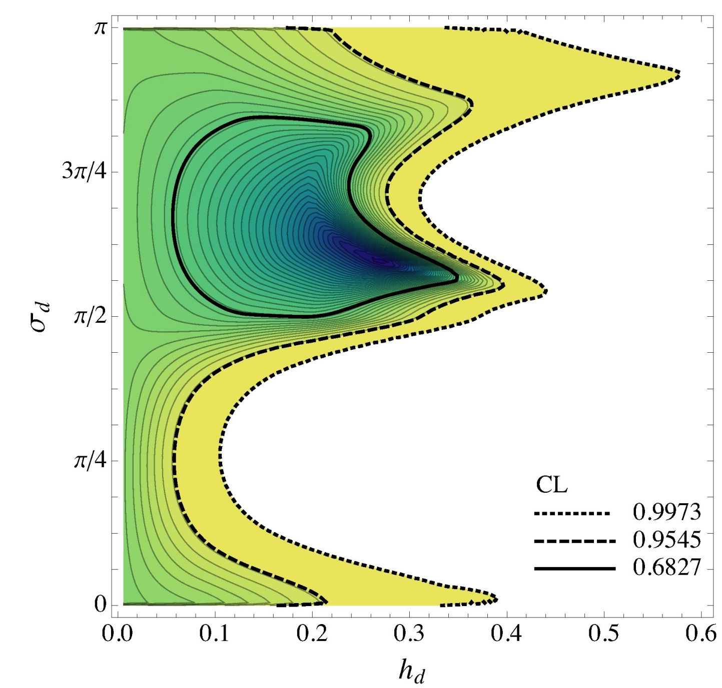
  - Inclusive dimuon asymmetry sensitive to NP in both B and B_s mixing

Ligeti et al. 1006.0432

  - Parameterize NP:

$$\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM}\left|1 + h_q e^{2i\sigma_q}\right|, \\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM} \cos\left[\arg\left(1 + h_s e^{2i\sigma_s}\right)\right], \\
A^q_{\rm SL} &= {\rm Im}\left\{\Gamma^q_{12}/\left[M^{q,{\rm SM}}_{12}(1 + h_q e^{2i\sigma_q})\right]\right\}, \\
S_{\psi K} &= \sin\left[2\beta + \arg\left(1 + h_d e^{2i\sigma_d}\right)\right], \\
S_{\psi\phi} &= \sin\left[2\beta_s - \arg\left(1 + h_s e^{2i\sigma_s}\right)\right].
\end{aligned}$$





  - Representative limits:

(a) $h_d = h_s$, $\sigma_d = \sigma_s$ OK, not preferred

(b) $h_s > h_d$ Preferred

Recent developments in the B_s system

- Theoretical interpretation: *NP in B_s mixing hypothesis*
  - If no CPV in decays, consistency relation between observables

Grossman, Nir, Perez, 0904.0305

$$a^s_{\rm SL} = -\frac{|\Delta\Gamma_s|}{\Delta m_s} S_{\psi\phi} \Big/ \sqrt{1 - S^2_{\psi\phi}} \qquad (S_{\psi\phi} = \sin 2\beta^{\rm eff}_s)$$

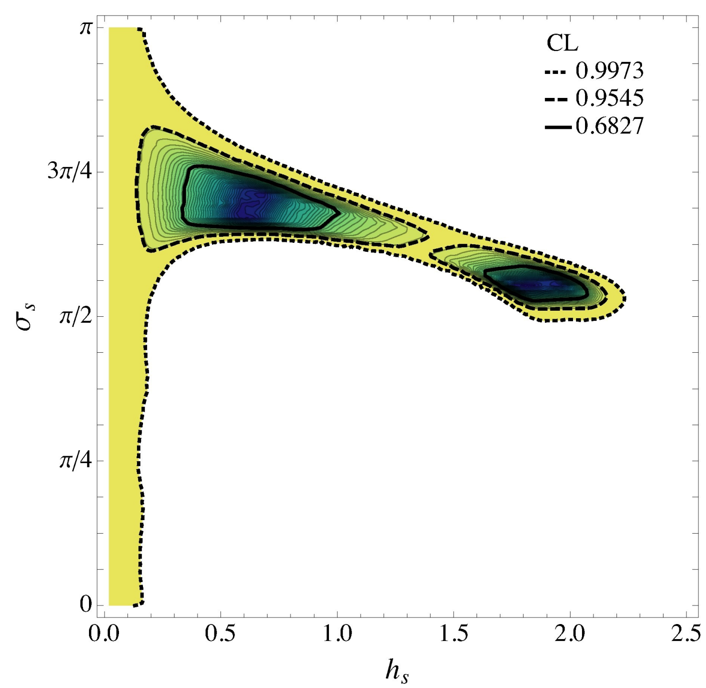
✔ Satisfied by current measurements

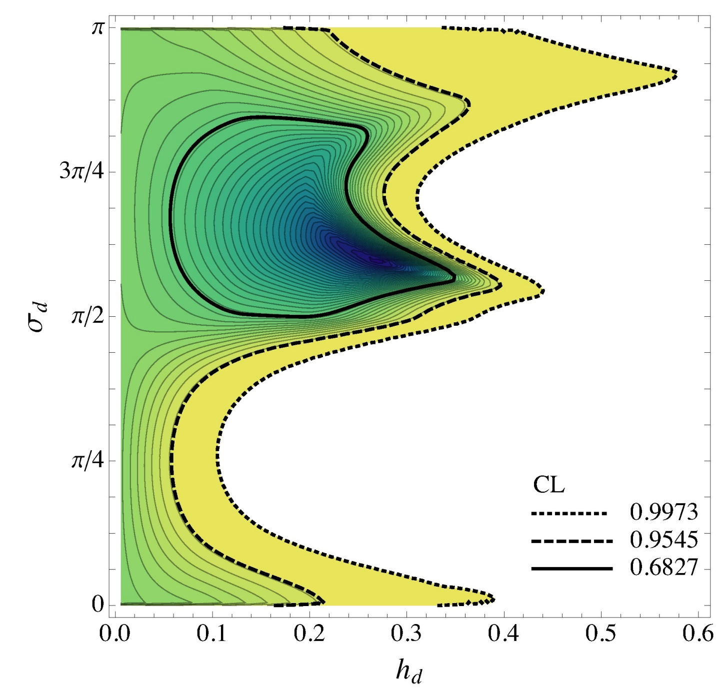
  - Inclusive dimuon asymmetry sensitive to NP in both B and B_s mixing

Ligeti et al. 1006.0432

- Parameterize NP:

$$\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM} \left|1 + h_q e^{2i\sigma_q}\right| , \\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM} \cos\left[\arg\left(1 + h_s e^{2i\sigma_s}\right)\right] , \\
A^q_{\rm SL} &= {\rm Im}\left\{\Gamma^q_{12}/\left[M_{12}^{q,{\rm SM}}(1 + h_q e^{2i\sigma_q})\right]\right\} , \\
S_{\psi K} &= \sin\left[2\beta + \arg\left(1 + h_d e^{2i\sigma_d}\right)\right] , \\
S_{\psi\phi} &= \sin\left[2\beta_s - \arg\left(1 + h_s e^{2i\sigma_s}\right)\right] .
\end{aligned}$$





- Representative limits:

(a) $h_d = h_s$, $\sigma_d = \sigma_s$ OK, not preferred

(b) $h_s > h_d$ Preferred

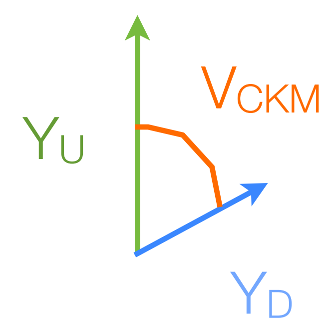
Need flavor non-universal new sources of CPV

Implications for minimal flavor violating NP

- Most conservative and agnostic approach to NP: EFT with MFV

D'Ambrosio et al.
hep-ph/0207036

    - SM gauge sector is invariant under a large flavor symmetry ($G_F \sim U(3)^5$) only broken by the Yukawa sector $Y_D = \lambda_d$, $Y_L = \lambda_\ell$, $Y_U = V_{CKM}^\dagger \lambda_u$

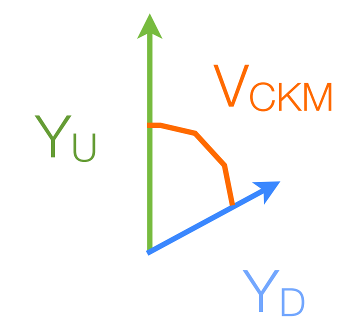


Implications for minimal flavor violating NP

- Most conservative and agnostic approach to NP: EFT with MFV

D'Ambrosio et al.
hep-ph/0207036

  - SM gauge sector is invariant under a large flavor symmetry ($G_F \sim U(3)^5$) only broken by the Yukawa sector $Y_D = \lambda_d$, $Y_L = \lambda_\ell$, $Y_U = V_{CKM}^\dagger \lambda_u$



  - MFV requires all higher dimensional operators to formally respect G_F – new flavor violating structures can only be constructed using polynomials of Y_i

  - Ratios of FCNC transitions among different generations are SM-like determined by CKM ($V_{ti}V_{tj}^*$) - NP shifts to SM predictions are flavor universal

$$H_{\Delta F=2} = (G_F^2\, m_W^2 / 8\pi^2)\, (V_{ti}V_{tj}^*)^2\, C_0\, [d_i\gamma_\mu(1-\gamma_5)d_j]^2$$

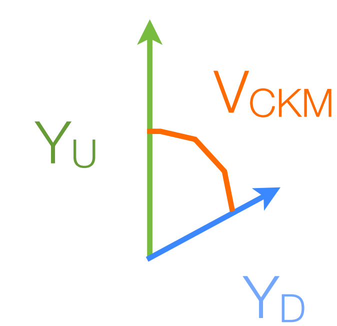
$$C_0(\mu_W) \to C_0(\mu_W)_{SM}\, [= S_0(x_t)/2] + \delta C_0$$

Implications for minimal flavor violating NP

- Most conservative and agnostic approach to NP: EFT with MFV

D'Ambrosio et al. hep-ph/0207036

  - SM gauge sector is invariant under a large flavor symmetry ($G_F \sim U(3)^5$) only broken by the Yukawa sector $Y_D = \lambda_d$, $Y_L = \lambda_\ell$, $Y_U = V_{CKM}^\dagger \lambda_u$



  - MFV requires all higher dimensional operators to formally respect G_F – new flavor violating structures can only be constructed using polynomials of Y_i

  - Ratios of FCNC transitions among different generations are SM-like determined by CKM ($V_{ti}V_{tj}^*$) - NP shifts to SM predictions are flavor universal

  - Right-handed quark operators helicity suppressed (like in SM)

CKM as the only source of CPV is an additional assumption!

MFV and new sources of CPV

- Even within SM, CKM not the only source of CPV: $\mathcal{L}_{QCD} \ni \frac{n_f \theta \alpha_s}{8\pi} \mathrm{Tr} G_{\mu\nu} \widetilde{G}^{\mu\nu}$
  - Contributes to electric dipole moment of neutron ($d_n < 0.29 \times 10^{-25}$ e cm)

    Baker et al.
    hep-ex/0602020
  - Source of 10^{-10} fine-tuning between θ and overall chiral quark phase in Y_i

MFV and new sources of CPV

- Even within SM, CKM not the only source of CPV: $$\mathcal{L}_{QCD} \ni \frac{n_f \theta \alpha_s}{8\pi} \mathrm{Tr} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$
  - Contributes to electric dipole moment of neutron ($d_n < 0.29 \times 10^{-25}$ e cm) Baker et al. hep-ex/0602020
  - Source of 10^{-10} fine-tuning between θ and overall chiral quark phase in Y_i
- In MFV, NP contributions δC_i can in principle be complex
  - Would naively expect severe constraints on Im[δC_i] from d_n and diagonal entries in Y expansion - no measurable effects in flavor observables?

MFV and new sources of CPV

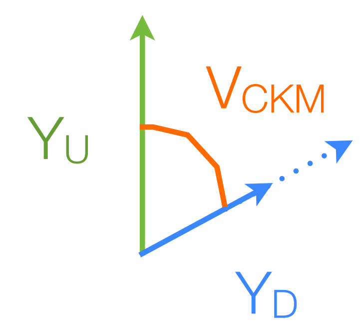
- Even within SM, CKM not the only source of CPV: $$\mathcal{L}_{QCD} \ni \frac{n_f \theta \alpha_s}{8\pi} \mathrm{Tr} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$
  - Contributes to electric dipole moment of neutron ($d_n < 0.29 \times 10^{-25}$ e cm) Baker et al. hep-ex/0602020
  - Source of 10^{-10} fine-tuning between θ and overall chiral quark phase in Y_i
- In MFV, NP contributions δC_i can in principle be complex
  - Would naively expect severe constraints on Im[δC_i] from d_n and diagonal entries in Y expansion - no measurable effects in flavor observables?
- In concrete NP models, natural cancellations in flavor diagonal contributions can occur - difficult to control in EFT

Mercolli & Smith, 0902.1949
Paradisi & Straub 0906.4551
Batell & Pospelov, 1006.2127
Buras et al., 1007.5291

- ΔF=1,2 operators decoupled in EFT - strongest bound on new phases in ΔF=2 from ε_K

Controlled breaking of flavor universality - GMFV

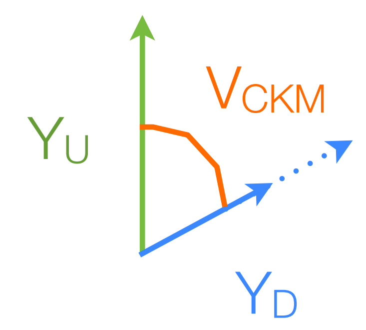
- In extended Higgs sectors, absence of FCNCs at tree level requires introduction of protective symmetry [Z_2, $U(1)_{PQ}$ in THDM]
    - Individual Higgs doublets [$H_{u,d}$] couple exclusively to up or down sectors
    - $\tan\beta = v_u/v_d$ - allows for rescaling of down-type Yukawas ($v^2=v_u^2+v_d^2$)



- Breaking of $U(1)_{PQ}$ can respect G_F - satisfies MFV

Controlled breaking of flavor universality - GMFV

- In extended Higgs sectors, absence of FCNCs at tree level requires introduction of protective symmetry [Z_2, $U(1)_{PQ}$ in THDM]
  - Individual Higgs doublets [$H_{u,d}$] couple exclusively to up or down sectors
  - $\tan\beta = v_u/v_d$ - allows for rescaling of down-type Yukawas ($v^2=v_u^2+v_d^2$)

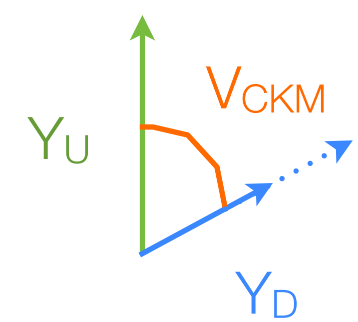


- Breaking of $U(1)_{PQ}$ can respect G_F - satisfies MFV
- $\lambda_b \sim m_b \tan\beta$ driven effects may become important, re-summation effects may decouple K, B sectors

May reproduce limit (a)

Controlled breaking of flavor universality - GMFV

- In extended Higgs sectors, absence of FCNCs at tree level requires introduction of protective symmetry [Z_2, $U(1)_{PQ}$ in THDM]
    - Individual Higgs doublets [$H_{u,d}$] couple exclusively to up or down sectors
    - $\tan\beta = v_u/v_d$ - allows for rescaling of down-type Yukawas ($v^2=v_u^2+v_d^2$)



- Breaking of $U(1)_{PQ}$ can respect G_F - satisfies MFV
- $\lambda_b \sim m_b \tan\beta$ driven effects may become important, re-summation effects may decouple K, B sectors

May reproduce limit (a)

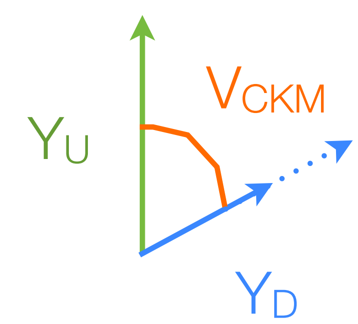
- New operator contributions
    - $[\lambda_b \bar{b}(1-\gamma_5)d_j]\ [\lambda_\ell \bar{\ell}(1-\gamma_5)\ell]$ - new contributions to $B \to X_s \ell^+ \ell^-$, $B_s \to \mu^+\mu^-$

May reproduce limit (b)

- $[\lambda_b \bar{b}(1-\gamma_5)d_j]\ [\lambda_{dj} \bar{d}_j(1-\gamma_5)b]$ - breaks universality between K and B_q sectors in $\Delta F=2$ FCNCs

Controlled breaking of flavor universality - GMFV

- In extended Higgs sectors, absence of FCNCs at tree level requires introduction of protective symmetry [Z_2, $U(1)_{PQ}$ in THDM]
  - Individual Higgs doublets [$H_{u,d}$] couple exclusively to up or down sectors
  - $\tan\beta = v_u/v_d$ - allows for rescaling of down-type Yukawas ($v^2=v_u^2+v_d^2$)



- Breaking of $U(1)_{PQ}$ can respect G_F - satisfies MFV
- $\lambda_b \sim m_b \tan\beta$ driven effects may become important, re-summation effects may decouple K, B sectors

May reproduce limit (a)

  - New operator contributions
    - $[\lambda_b \bar{b}(1-\gamma_5)d_j]\,[\lambda_\ell \bar{\ell}(1-\gamma_5)\ell]$ - new contributions to $B\to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
    - $[\lambda_b \bar{b}(1-\gamma_5)d_j]\,[\lambda_{dj} \bar{d}_j(1-\gamma_5)b]$ - breaks universality between K and B_q sectors in $\Delta F=2$ FCNCs

May reproduce limit (b)

Kagan et al. 0903.1794

Buras et al, 1005.5310

In GMFV, new operator contributions only relevant in the B sector, can provide new sources of CPV in B_q mixing - may scale with λ_q

GMFV can account for CPV in B_s

Implications for rare B decays?

ΔB=1 FCNCs

- Many operators contributing, several observables available

$$\mathcal{H}_{eff}^{\Delta F=1} = \frac{G_F \alpha_{em}}{2\sqrt{2}\pi \sin^2\theta_W} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}$$

EM and QCD dipole operators

$$\mathcal{Q}_{7\gamma} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} d_{jR} (e F_{\mu\nu}) \qquad \mathcal{Q}_{8G} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} T^a d_{jR} (g_s G^a_{\mu\nu})$$

EW-penguin operators

$$\mathcal{Q}_{9V} = 2\bar{d}_{iL}\gamma_\mu d_{jL}\, \bar{\ell}\gamma_\mu \ell \qquad \mathcal{Q}_{10A} = 2\bar{d}_{iL}\gamma_\mu d_{jL}\, \bar{\ell}\gamma_\mu\gamma_5 \ell$$

density operator at large $\tan\beta$

$$\mathcal{Q}_{S-P} = 4(\bar{d}_{iL} d_{jR})(\bar{\ell}_R \ell_L)$$

Z-penguin operator

$$\mathcal{Q}_{\nu\bar{\nu}} = 4\bar{d}_{iL}\gamma_\mu d_{jL} \bar{\nu}_L \gamma_\mu \nu_L$$

Direct correlations with ΔF=2 contributions not possible in EFT approach

Can test for indications of GMFV (large tan β)

ΔB=1 FCNCs

- Many operators contributing, several observables available

$$\mathcal{H}_{eff}^{\Delta F=1} = \frac{G_F \alpha_{em}}{2\sqrt{2}\pi \sin^2\theta_W} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n \; + \; \text{h.c.}$$

EM and QCD dipole operators

$$\mathcal{Q}_{7\gamma} \; = \; \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} d_{jR} (e F_{\mu\nu}) \qquad \mathcal{Q}_{8G} \; = \; \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} T^a d_{jR} (g_s G^a_{\mu\nu})$$

Mostly constrained by $B \to X_s \gamma$

Discrete ambiguity correlated with Q_{9V}

Effective NP scale $\Lambda > 6(3)$ TeV

EW-penguin operators

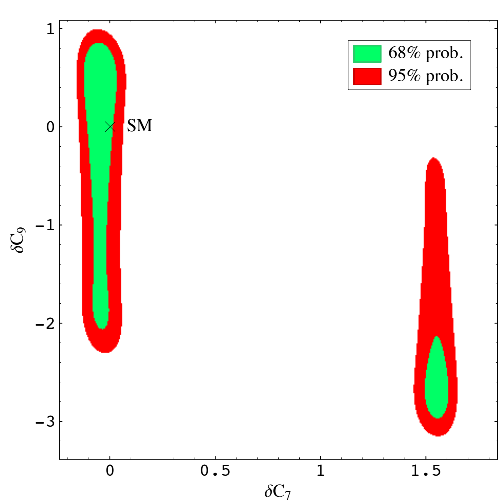
$$\mathcal{Q}_{9V} \; = \; 2\bar{d}_{iL}\gamma_\mu d_{jL} \; \bar{\ell}\gamma_\mu \ell \qquad \mathcal{Q}_{10A} \; = \; 2\bar{d}_{iL}\gamma_\mu d_{jL} \; \bar{\ell}\gamma_\mu \gamma_5 \ell$$

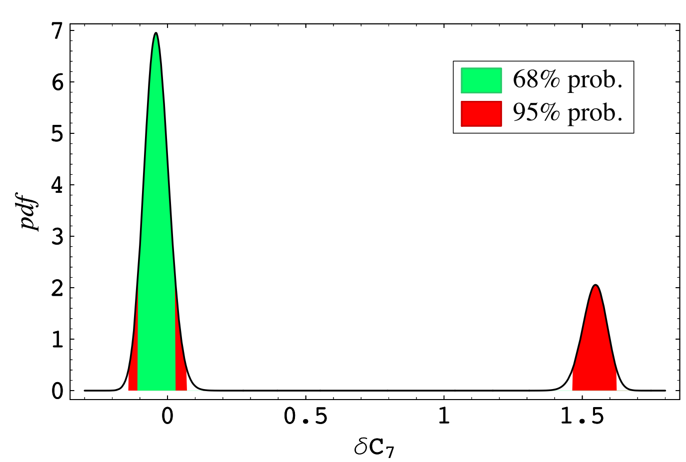
density operator at large $\tan\beta$

$$\mathcal{Q}_{S-P} \; = \; 4(\bar{d}_{iL} d_{jR})(\bar{\ell}_R \ell_L)$$

Z-penguin operator

$$\mathcal{Q}_{\nu\bar{\nu}} \; = \; 4\bar{d}_{iL}\gamma_\mu d_{jL} \bar{\nu}_L \gamma_\mu \nu_L$$





Hurth, Isidori, J.F.K. & Mescia, 0807.5039

ΔB=1 FCNCs

- Many operators contributing, several observables available

$$\mathcal{H}_{eff}^{\Delta F=1} = \frac{G_F \alpha_{em}}{2\sqrt{2}\pi \sin^2\theta_W} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n \; + \; \text{h.c.}$$

EM and QCD dipole operators

$$\mathcal{Q}_{7\gamma} \; = \; \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} d_{jR} (e F_{\mu\nu}) \qquad \mathcal{Q}_{8G} \; = \; \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} T^a d_{jR} (g_s G^a_{\mu\nu})$$

EW-penguin operators

$$\mathcal{Q}_{9V} \; = \; 2\bar{d}_{iL}\gamma_\mu d_{jL} \; \bar{\ell}\gamma_\mu \ell \qquad \mathcal{Q}_{10A} \; = \; 2\bar{d}_{iL}\gamma_\mu d_{jL} \; \bar{\ell}\gamma_\mu\gamma_5 \ell$$

density operator at large $\tan\beta$

$$\mathcal{Q}_{S-P} \; = \; 4(\bar{d}_{iL} d_{jR})(\bar{\ell}_R \ell_L)$$

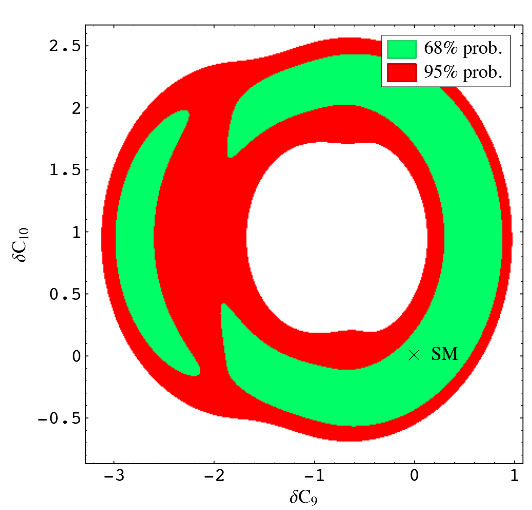
Z-penguin operator

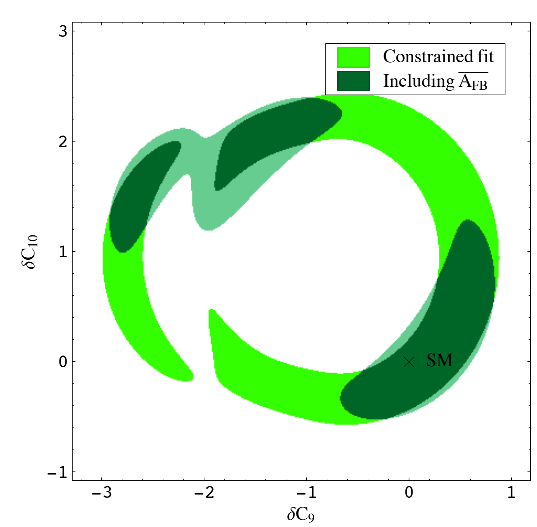
$$\mathcal{Q}_{\nu\bar{\nu}} \; = \; 4\bar{d}_{iL}\gamma_\mu d_{jL} \bar{\nu}_L \gamma_\mu \nu_L$$

Mostly constrained by $B \to X_s \ell^+ \ell^-$

Correlated ambiguity, (importance of A_{FB})

Effective NP scale $\Lambda >$ 1-3 TeV





Hurth, Isidori, J.F.K. & Mescia, 0807.5039

ΔB=1 FCNCs

- Many operators contributing, several observables available

$$\mathcal{H}_{eff}^{\Delta F=1} = \frac{G_F \alpha_{em}}{2\sqrt{2}\pi \sin^2\theta_W} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n + \text{h.c.}$$

EM and QCD dipole operators

$$\mathcal{Q}_{7\gamma} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} d_{jR} (e F_{\mu\nu}) \qquad \mathcal{Q}_{8G} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} T^a d_{jR} (g_s G^a_{\mu\nu})$$

EW-penguin operators

$$\mathcal{Q}_{9V} = 2\bar{d}_{iL}\gamma_\mu d_{jL}\ \bar{\ell}\gamma_\mu \ell \qquad \mathcal{Q}_{10A} = 2\bar{d}_{iL}\gamma_\mu d_{jL}\ \bar{\ell}\gamma_\mu\gamma_5 \ell$$

density operator at large $\tan\beta$

$$\mathcal{Q}_{S-P} = 4(\bar{d}_{iL} d_{jR})(\bar{\ell}_R \ell_L)$$

Z-penguin operator

$$\mathcal{Q}_{\nu\bar{\nu}} = 4\bar{d}_{iL}\gamma_\mu d_{jL} \bar{\nu}_L \gamma_\mu \nu_L$$

Constrained by
$K^+ \to \pi^+ \nu\nu$

In the future
$B \to K^{(*)} \nu\nu$ important

Effective NP scale
$\Lambda > 1$ TeV

Hurth, Isidori, J.F.K. & Mescia, 0807.5039

ΔB=1 FCNCs

- Many operators contributing, several observables available

$$\mathcal{H}_{eff}^{\Delta F=1} = \frac{G_F \alpha_{em}}{2\sqrt{2}\pi \sin^2\theta_W} V_{ti}^* V_{tj} \sum_n C_n \mathcal{Q}_n \; + \; \text{h.c.}$$

EM and QCD dipole operators

$$\mathcal{Q}_{7\gamma} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} d_{jR} (e F_{\mu\nu}) \qquad \mathcal{Q}_{8G} = \frac{2}{g^2} m_j \bar{d}_{iL} \sigma_{\mu\nu} T^a d_{jR} (g_s G^a_{\mu\nu})$$

EW-penguin operators

$$\mathcal{Q}_{9V} = 2\bar{d}_{iL}\gamma_\mu d_{jL} \; \bar{\ell}\gamma_\mu \ell \qquad \mathcal{Q}_{10A} = 2\bar{d}_{iL}\gamma_\mu d_{jL} \; \bar{\ell}\gamma_\mu\gamma_5 \ell$$

density operator at large $\tan\beta$

$$\mathcal{Q}_{S-P} = 4(\bar{d}_{iL} d_{jR})(\bar{\ell}_R \ell_L)$$

Z-penguin operator

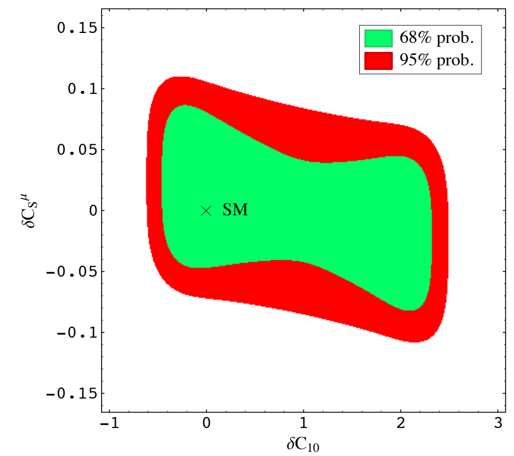
$$\mathcal{Q}_{\nu\bar{\nu}} = 4\bar{d}_{iL}\gamma_\mu d_{jL} \bar{\nu}_L \gamma_\mu \nu_L$$

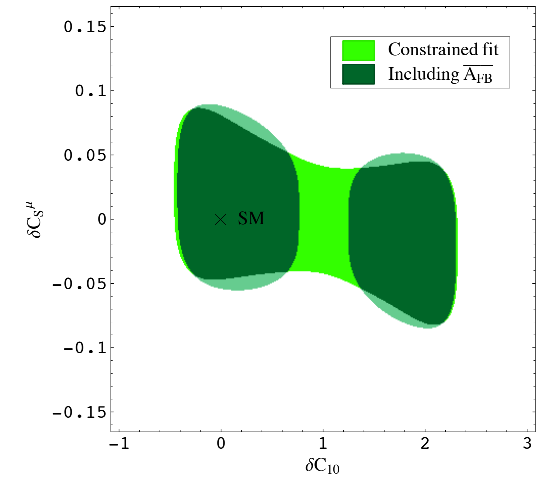
Mostly constrained by $B_s \to \mu^+\mu^-$

Correlation with Q_{10A}
(importance of A_{FB} in $B \to K^* \ell^+ \ell^-$)

Effective Charged Higgs scale
$\Lambda > 1.5\,(\tan\beta/50)^{3/2}$ TeV

Hurth, Isidori, J.F.K. & Mescia, 0807.5039





$b \to s \ell^+ \ell^-$

- Theoretical status

Huber et al., hep-ph/0512066, 0712.3009

  - Inclusive calculation at NNLO ($\alpha_s^2, \alpha_s \alpha_{EM}, \Lambda_{QCD}/m_b$)
    - low 1 GeV$^2 < q^2 <$ 6 GeV^2 - precision at 8%
    - high $q^2 >$ 14.4 GeV^2 region - large power corrections, precision at 30%
  - Exclusive modes $B \to K^{(*)} l^+ l^-$ approached using QCDF(SCET) + local form factors (QCDSR, LQCD) - applicable to the low q^2 region
    - Zero of FBA precisely predicted in the SM

Beneke et al., hep-ph/0106067, hep-ph/0412400

    - Full angular amplitude analysis allows to discriminate new CPV, right-handed current contributions

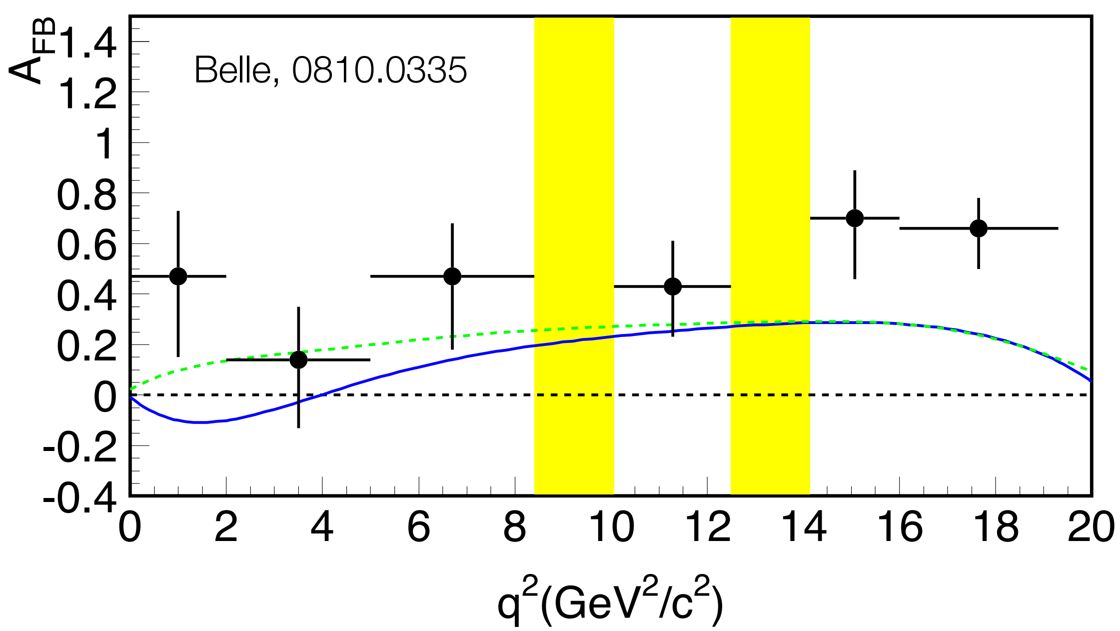
Egede et al., 0807.2589
Altmannshofer et al., 0811.1214
Egede et al., 1005.0571

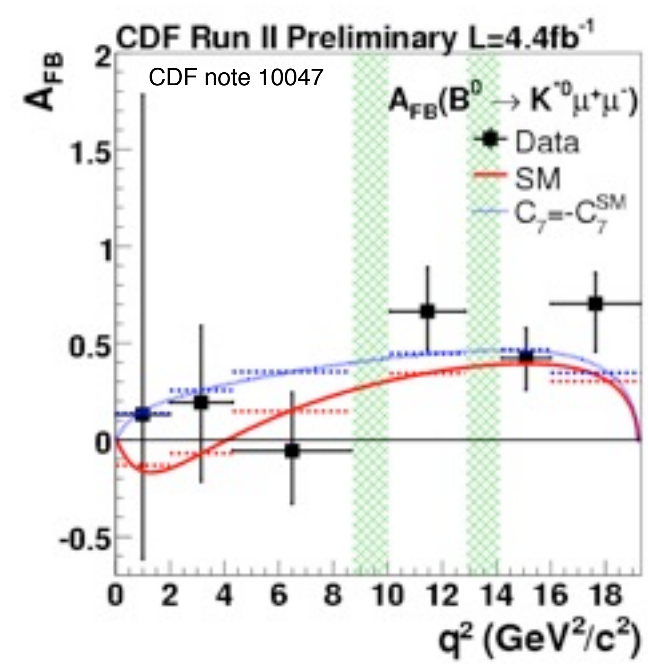
      - Feasible at the SuperB factories

Possibility of testing (G)MFV, new CPV sources

New physics in b → s $\ell^+ \ell^-$

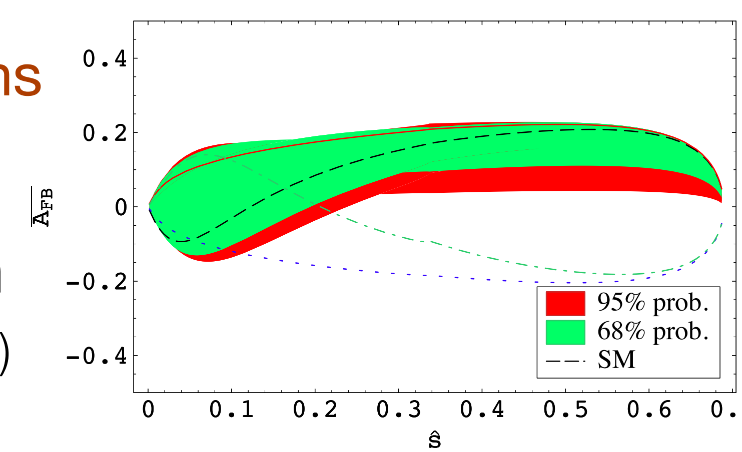
- Comparing with present experimental measurements
  - Hints of anomalously large positive FBA in exclusive ($B \rightarrow K^* \ell^+ \ell^-$) reported at both low and high q^2





also
BaBar, 0804.4412
Belle, 0904.0770

  - Not trivial to reconcile with other (inclusive $B \rightarrow X_s \ell^+ \ell^-$, $B \rightarrow X_s\gamma$) measurements
  - C_7=-C_7^{SM} scenario without simultaneous large corrections to $C_{9,10}$ (or new operator contributions) is excluded

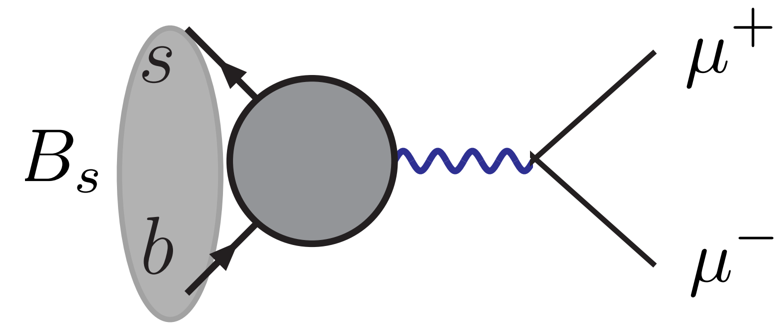


- Other observables (F_L, A_l) less sensitive at present precision

(Also theoretically limited)

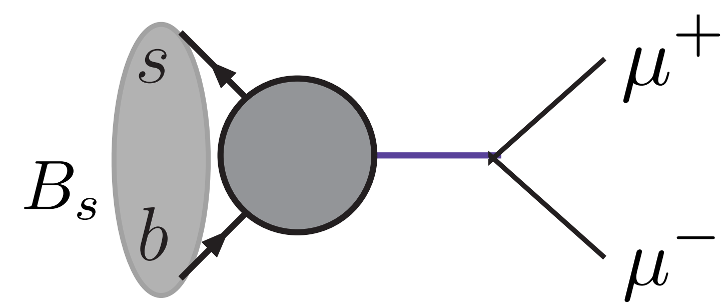
$B_{s/d} \to \ell^+ \ell^-$

- Helicity suppressed in the SM

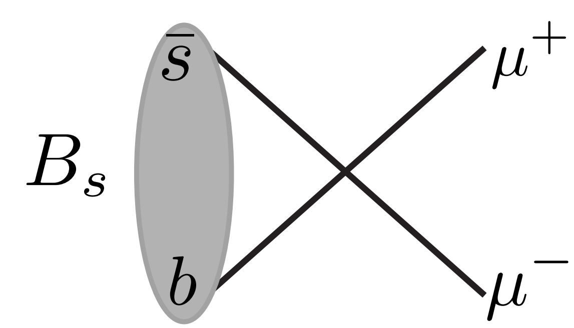


  - mediated by short-distance Z penguin and box
  - long distance strongly CKM / GIM suppressed
  - main uncertainties: B decay constant, CKM

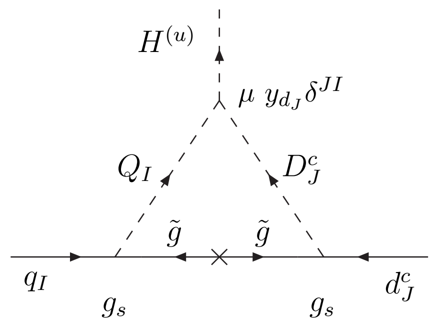
- NP can $\frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2 \theta_W} V_{tb}^* V_{tq} \left[C_S Q_S + C_P Q_P + C_A Q_A \right]$



  - modify the Z penguin
  - induce a Higgs penguin or new contact interactions (possibly lifting helicity suppression)



New physics in $B_{s/d} \to \ell^+ \ell^-$



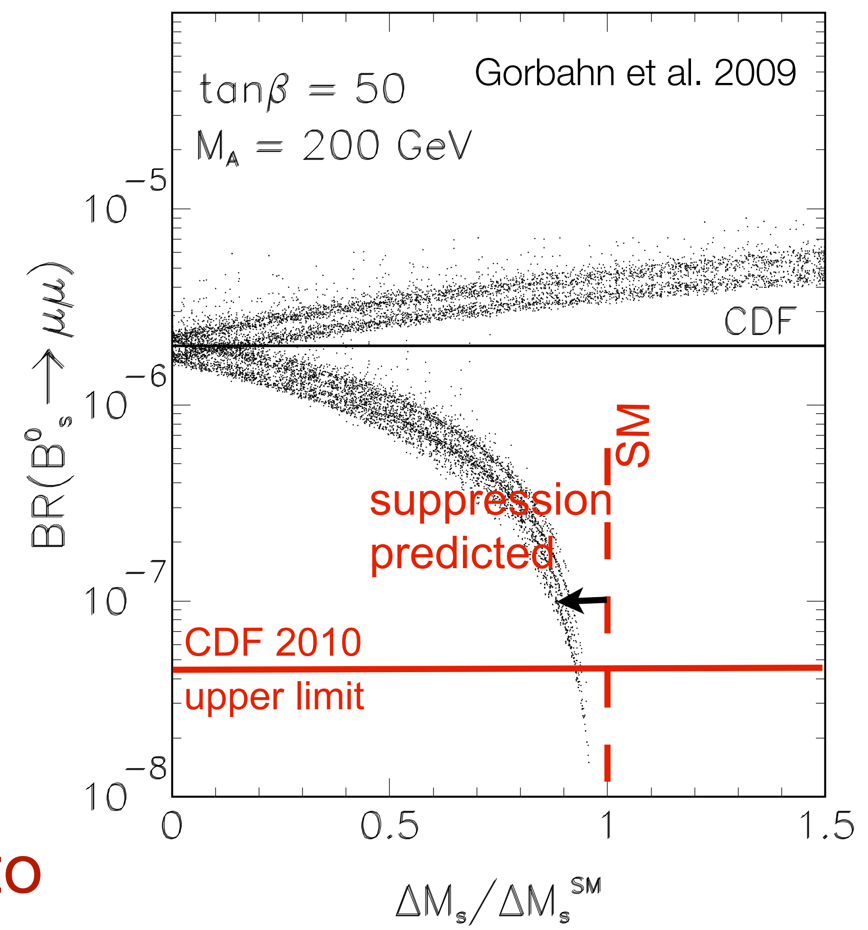
- Example: MSSM at large tanβ

[Choudhury&Gaur 99; Hamzaoui, Pospelov, Toharia 99; Babu, Kolda 99; Isidori, Retico; Buras et al 02; Foster et al 04-06,...]

  - Flavor violating ($U(1)_{PQ}$ breaking) Yukawa interactions induced at loop level - tanβ² enhanced: $BR(B_s \to \mu\mu) \propto \tan^6 \beta$

  - In MFV MSSM, correlated with Δm_s: A. Buras, hep-ph/0303060

    - bound on $BR(B_s \to \mu^+\mu^-)$ constrains effects in B_s mixing - both primary measurements of LHCb



  - Beyond MFV, no correlations

    - $B_d \to \ell^+\ell^-$ not necessarily suppressed compared to $B_s \to \ell^+\ell^-$, possibility of LUV & LFV

B→ℓ ν and B→D(*)τν

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

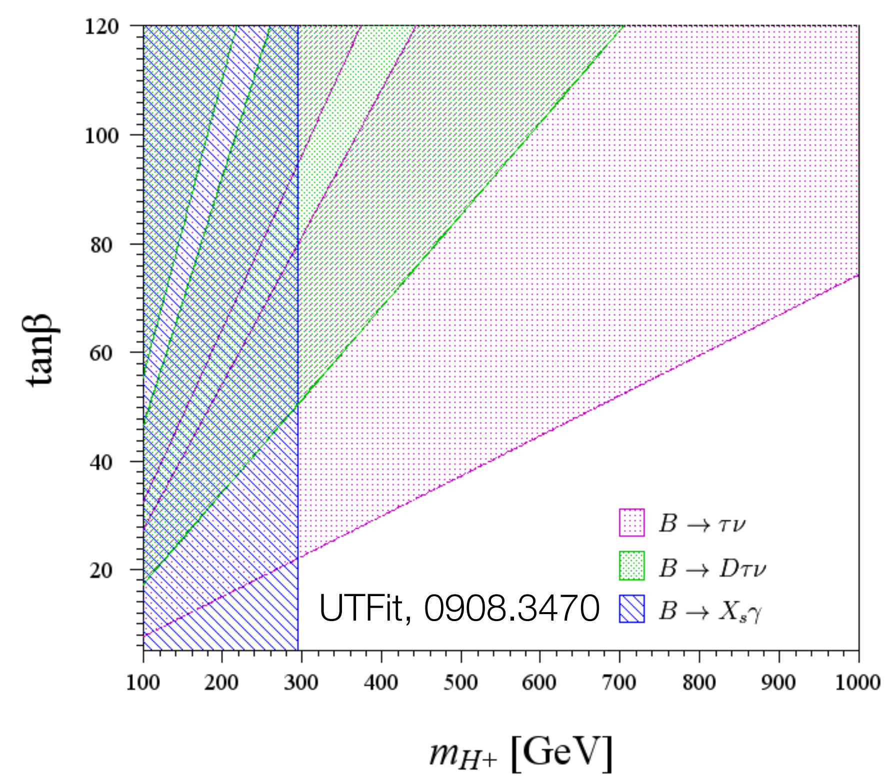
Hou, W.-S., 1993, Phys. Rev. D48, 2342.

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

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

- Example THDMII (MFV MSSM)

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



New physics in B→ℓ ν

- 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→ℓ ν

- Relevant for consistency check of V_{ub} extraction
  - Example: presence of right-handed currents will affect it differently than B→π ℓ ν or B→X_u ℓ ν

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

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

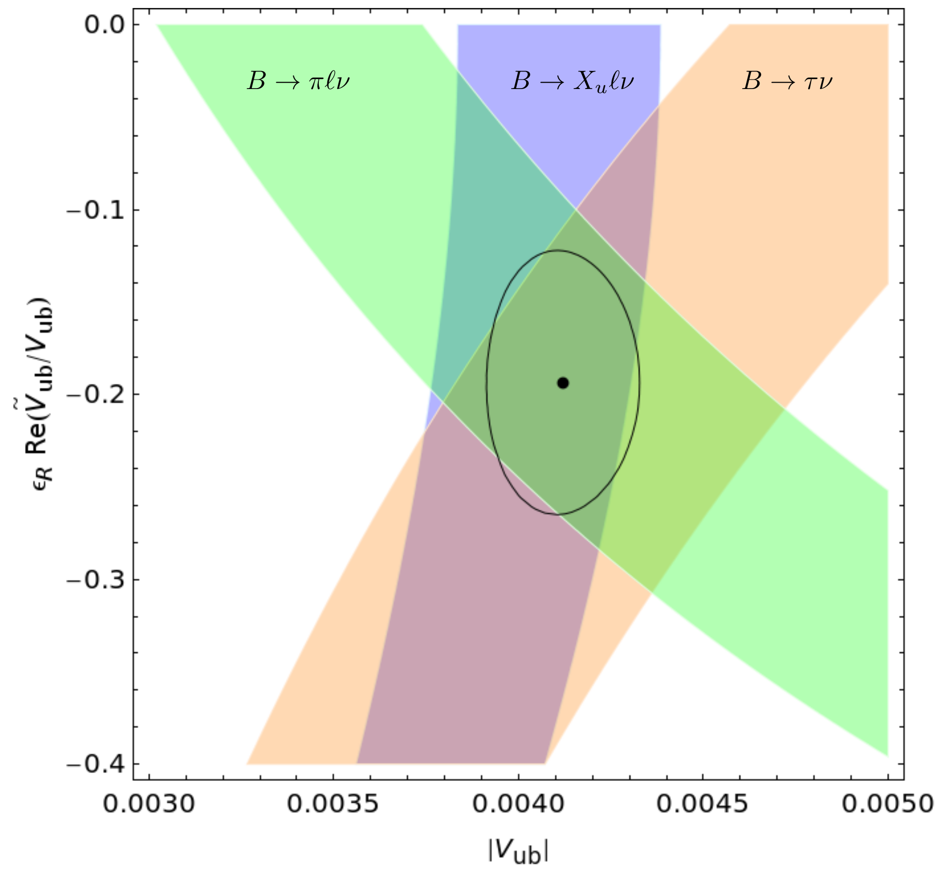
$$|V_{ub}|^{B\to\pi}_{\text{SM-exp}} = |V_{ub} + \epsilon_R\widetilde{V}_{ub}|$$

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

  - 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

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

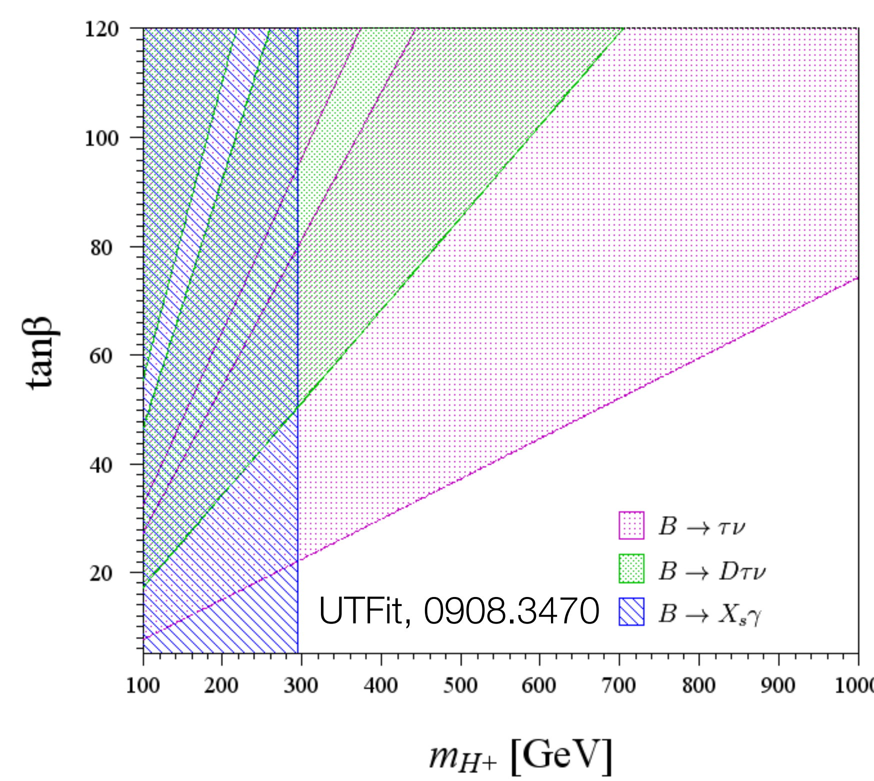
Kiers & Soni, hep-ph/9706337
Chen & Geng, JHEP 10, 053.
M. Tanaka, Z. Phys. C67, 321.

- 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

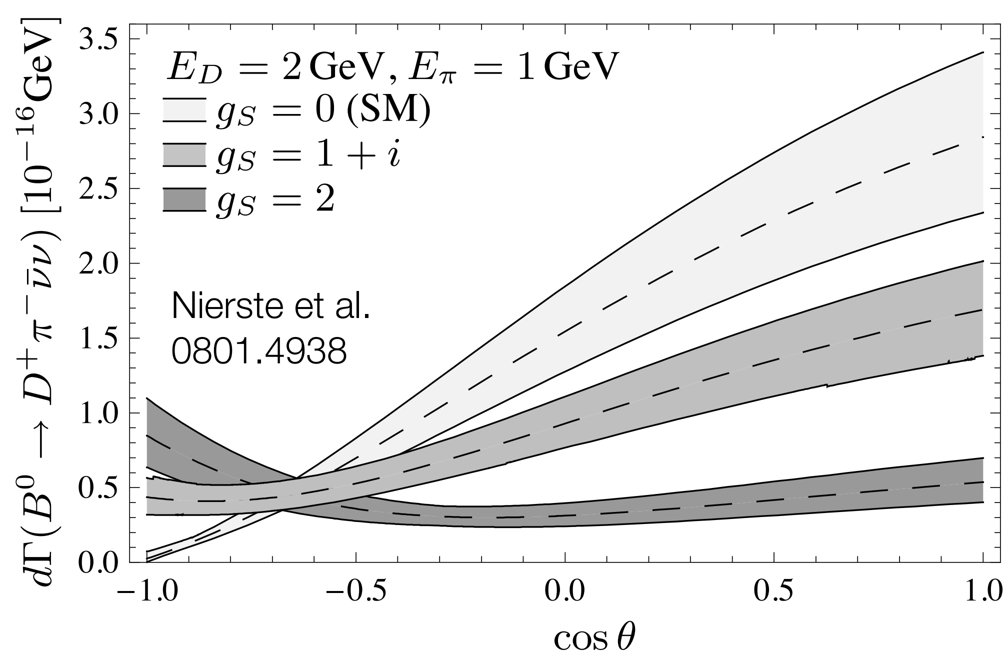
- Additional kinematical and lepton spin observables allow access to NP phases
  - Self analyzing virtue of tau - one can look at pion angle distribution in its two-body hadronic decay mode in $\bar{B} \to D\bar{\nu}_\tau \tau^- [\to \pi^- \nu_\tau]$
    - Example: angle between D and π in B rest frame

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

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

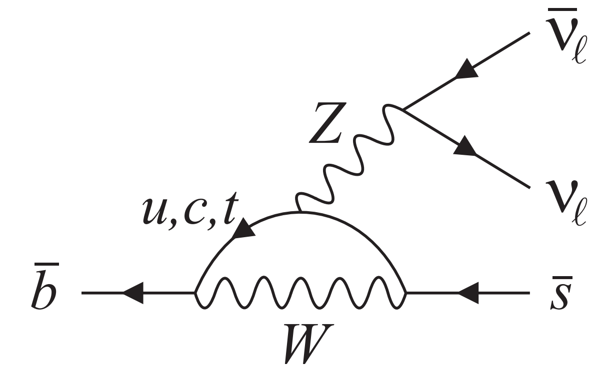
Nierste et al. 0801.4938

Tanaka & Watanabe 1005.4306



Discriminates between CPV phase of charged Higgs contribution

b → s/d νν



- **In SM:** Z-penguin observable

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^* \,(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu) \;\; + \;\; \text{h.c.}$$

$$O_L^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\;, \quad O_R^\nu = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

  - Leading short distance contribution known to ~1%: $(C_L^\nu)^{\rm SM} = -6.33 \pm 0.06$

    Brod et al., 1009.0947

  - Absence of photonic penguin operator which dominates b → s $\ell^+\ell^-$ at low q^2

- **Beyond SM:** b → s/d $E_{\rm miss}$ experimental signature allows to probe new light SM singlet particles

b → s/d νν observables

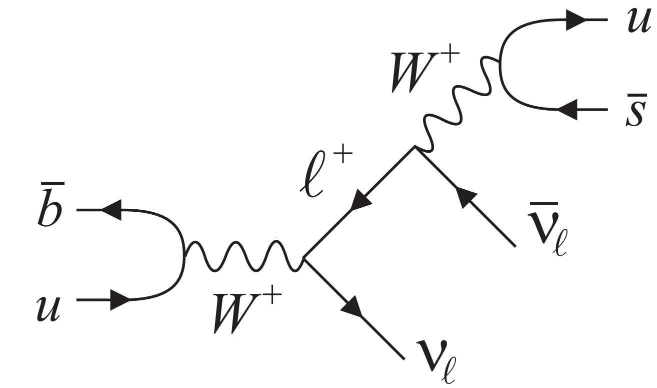
- Inclusive B → Xs,d νν: Theoretically cleanest (HQE & OPE) - Experimentally challenging
- $B^+ \to K^+ \nu\nu$ presently provides most stringent bound on NP (x3 SM)
  - SuperB could reach 3σ with $10ab^{-1}$, while $50ab^{-1}$ needed for B → K* mode

SuperB progress reports: Physics 1008.1541

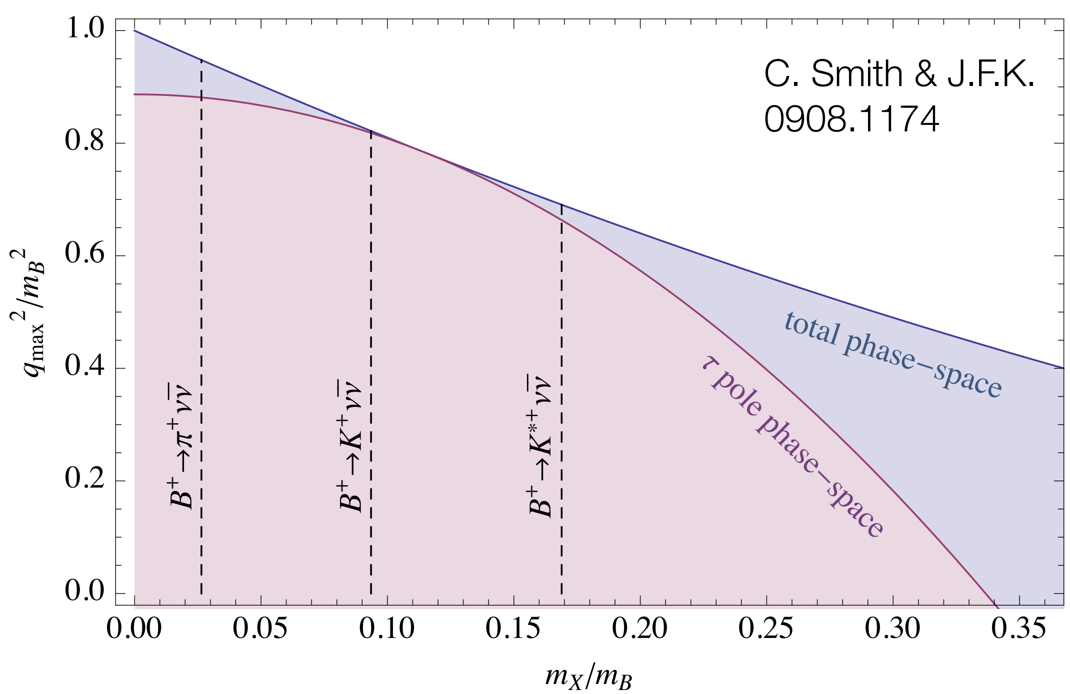
- K* final state offers additional observable
  - longitudinal/transverse polarization fractions $F_{L,T} = \frac{d\Gamma_{L,T}/ds_B}{d\Gamma/ds_B}\ , \quad F_L = 1 - F_T$
  - experimentally accessible through angular distribution of K* decay products

$$\frac{d^2\Gamma}{ds_B d\cos\theta} = \frac{3}{4}\frac{d\Gamma_T}{ds_B}\sin^2\theta + \frac{3}{2}\frac{d\Gamma_L}{ds_B}\cos^2\theta\ .$$

LD contributions to $B^+ \to K^{(*)+} \nu\nu$



- Important background from $B^+ \to \tau^+ \nu$ with tau decaying into $K^{(*)+} \nu$



Formally of order $G_F{}^4$ - compensated by narrow width of intermediate tau lepton

Account for 98% in $B^+ \to \pi^+ \nu\nu$
12% in $B^+ \to K^+ \nu\nu$
14% in $B^+ \to K^{*+} \nu\nu$

(Also affects inclusive $B \to X_{s,d}\, \nu\nu$)

- can be measured and subtracted

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{LD} \propto \mathcal{B}(B^+ \to \tau^+ \nu) \times \mathcal{B}(\tau^+ \to K^+ \bar{\nu})$$

- or can be computed and added (V_{ub}, $f_{B,K}$)

- Presently, the associated uncertainty is ~3(4)% in $B^+ \to K^{(*)+} \nu\nu$

Using decay constant estimates from:
V. Lubicz and C. Tarantino, 0807.4605
P. Ball, et al., hep-ph/0612081.

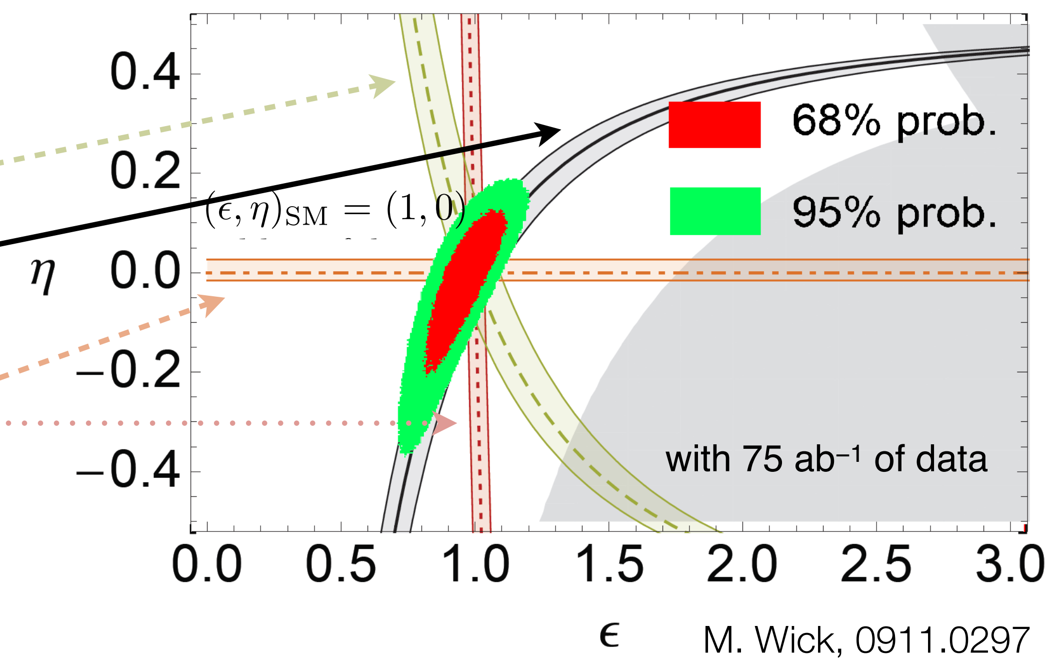
New physics in b → s/d νν

- Parametrize SM+NP in OPE: $\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu \right) \;+\; \text{h.c.}$

- Only two independent combinations measurable with present observables

$$\epsilon = \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|(C_L^\nu)^{\text{SM}}|}\,, \qquad \eta = \frac{-\text{Re}\,(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}$$

$$R(B \to K^* \nu\bar{\nu}) = (1 + 1.31\,\eta)\epsilon^2,$$
$$R(B \to K \nu\bar{\nu}) = (1 - 2\,\eta)\epsilon^2,$$
$$R(\bar{B} \to X_s \nu\bar{\nu}) = (1 + 0.09\,\eta)\epsilon^2,$$
$$\langle F_L \rangle / \langle F_L \rangle_{\text{SM}} = \frac{(1 + 2\,\eta)}{(1 + 1.31\,\eta)},$$
$$R(X) = \mathcal{B}(X)/\mathcal{B}(X)_{\text{SM}}$$



M. Wick, 0911.0297

- important feature of F_L: only depends on η

  - Any deviation from SM would imply presence of right-handed currents

Altmannshofer et al., 0902.0160

New physics in b → s/d νν

Y. Grossman et al.,
Nucl. Phys. B465, 369.

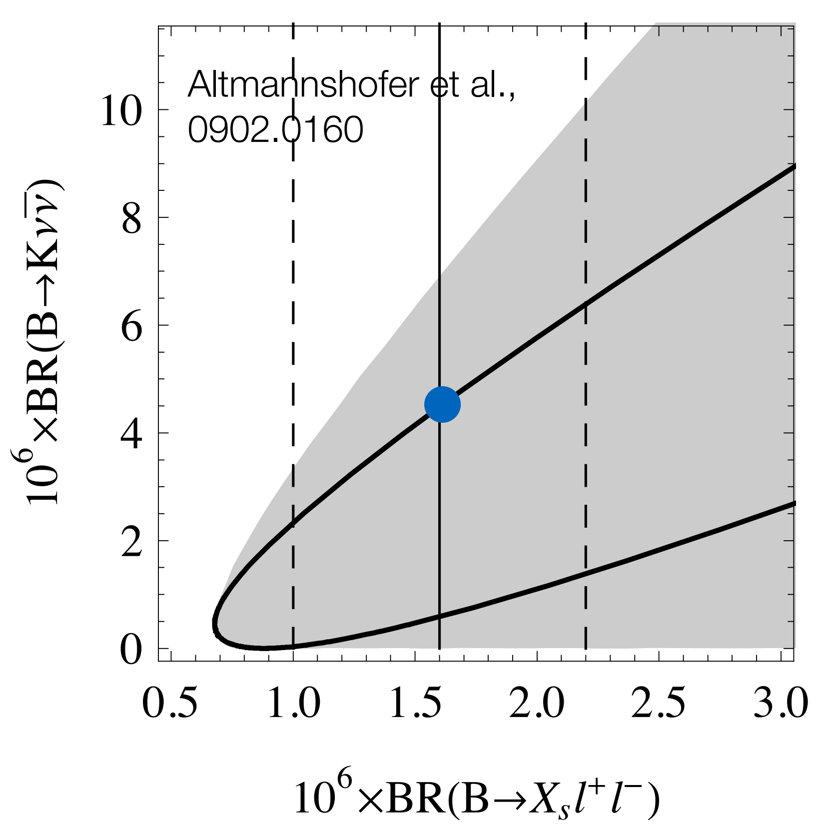
- Example: parameterize dominance of Z penguin via modified bsZ coupling

C. Bird, et al.,
Phys. Rev. Lett. 93, 201803.

- Correlations (constraints) from other b observables ($B_s \to \ell^+\ell^-$, $B \to X_s \ell^+\ell^-$)

G. Buchalla, et al.,
hep-ph/0006136

- b → s/d νν cannot be enhanced more than ~ SM x 2*



*or other NP contributions need to compensate $B \to X_s \ell^+\ell^-$

New physics in b → s/d νν

Y. Grossman et al.,
Nucl. Phys. B465, 369.

- Example: parameterize dominance of Z penguin via modified bsZ coupling

C. Bird, et al.,
Phys. Rev. Lett. 93, 201803.

  - Correlations (constraints) from other b observables ($B_s \to \ell^+\ell^-$, $B \to X_s\, \ell^+\ell^-$)

G. Buchalla, et al.,
hep-ph/0006136

Altmannshofer et al.,
0902.0160

  - b → s/d νν cannot be enhanced more than ~ SM x 2*

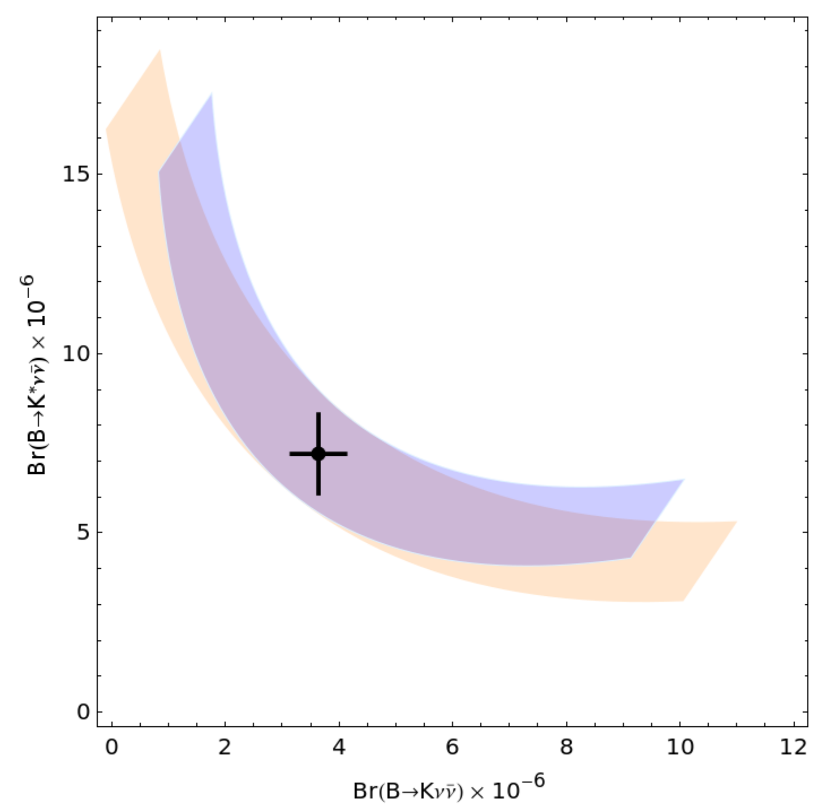
*or other NP contributions need to compensate $B \to X_s\, \ell^+\ell^-$

A. Buras et al., 1007.1993

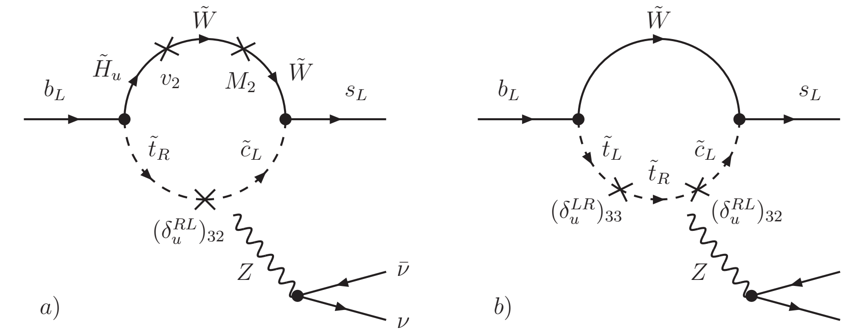
- (Sub)Example: New right handed sources of flavor violation
  - particular modification of Z couplings

    (motivated by the resolution of the $S_{\psi\phi}$ puzzle)

  - correlations among b → s/d νν modes



New physics in b → s/d νν



- In MSSM very constrained
  - gluino contributions constrained by $B \to X_s \gamma$
  - tanβ-enhanced Higgs contributions to C_R constrained by $B_s \to \mu^+\mu^-$
  - up-squark - chargino loops (δ_{RL}^{32}) can enhance/suppress Br ~ 35% (no effect in F_L)
- In RPV MSSM still room for large enhancements?

S. Bertolini, et al., Nucl. Phys. B353 (1991) 591–649.

T. Goto, et al., hep-ph/9609512

A. J. Buras, et al., hep-ph/0408142

Y. Yamada, 0709.1022

Isidori & Paradisi, hep-ph/0601094

Altmannshofer et al., 0902.0160

Kim, & Wang, 0904.0318

New physics in b → s/d E_{miss}

- Neutrinos not detected in experiments probing b → s/d νν
- Various NP contributions can mimic experimental signature

  very light scalar dark matter
  light neutralinos
  light NMSSM pseudoscalar Higgs
  light radions
  unparticles
  ...

C. Bird, et al., hep-ph/0401195.

R. Adhikari & B. Mukhopadhyaya, hep-ph/9411347.

H. K. Dreiner et al., 0905.2051.

G. Hiller, hep-ph/0404220.

H. Davoudiasl and E. Ponton, 0903.3410.

T. M. Aliev, et al., 0705.4542

- Failure of the individual constraints on the ε-η plane meeting at a single point
- Kinematical distributions modified - need to be taken into account when interpreting experimental searches
  - kinematical cuts to suppress backgrounds
  - reconstruction efficiencies depend on final state kaon/pion momenta

New physics in b → s/d E_{miss}

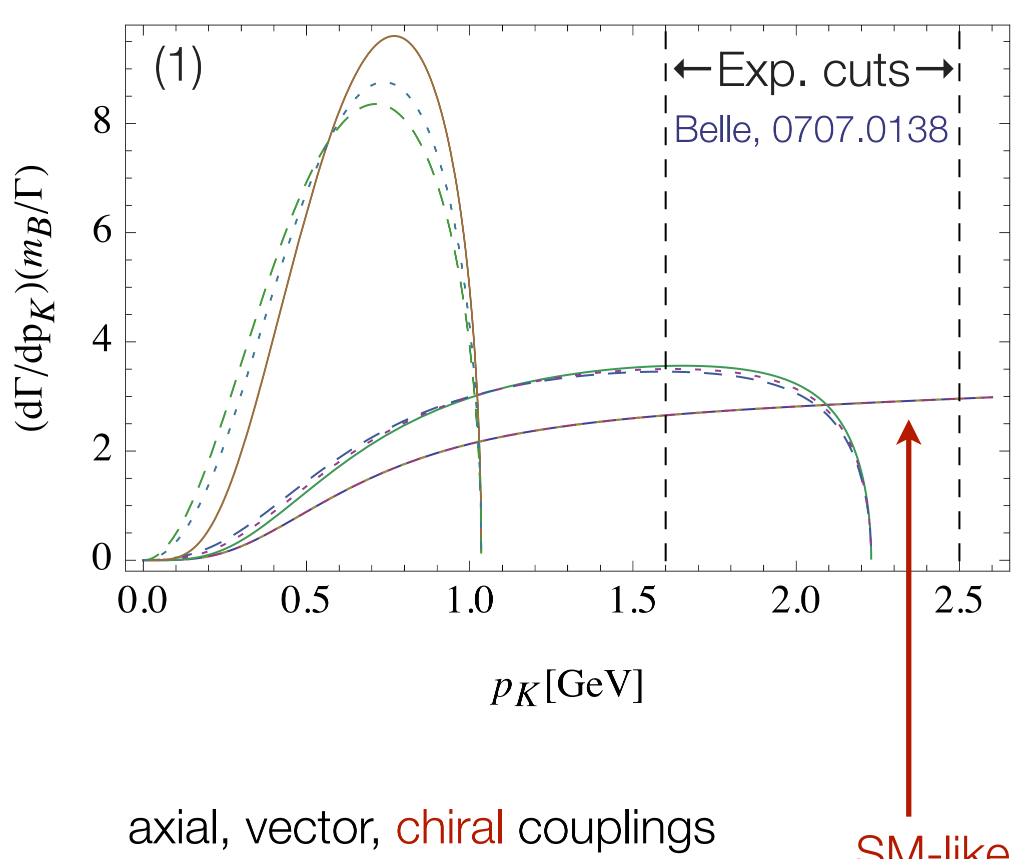
- Example: pair of invisible massive fermions in B→K E_{miss}

$$(1)\quad \frac{c_{11}^{1/2}}{\Lambda^2}(\bar{Q}\gamma_\mu Q)(\bar{\psi}\gamma^\mu\psi) + \frac{\tilde{c}_{11}^{1/2}}{\Lambda^2}(\bar{Q}\gamma_\mu Q)(\bar{\psi}\gamma^\mu\gamma_5\psi) + \frac{c_{12}^{1/2}}{\Lambda^2}(\bar{D}\gamma_\mu D)(\bar{\psi}\gamma^\mu\psi) + \frac{\tilde{c}_{12}^{1/2}}{\Lambda^2}(\bar{D}\gamma_\mu D)(\bar{\psi}\gamma^\mu\gamma_5\psi)$$

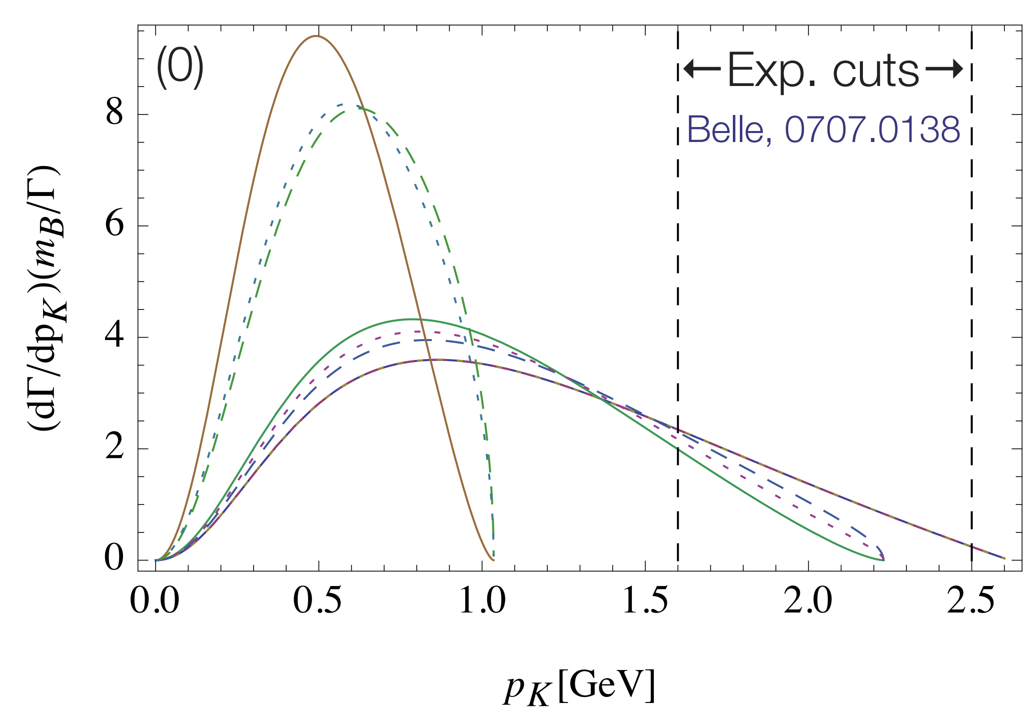
$$(0)\quad \frac{c_{01}^{1/2}}{\Lambda^3}H(\bar{D}Q)(\bar{\psi}\psi) + \frac{\tilde{c}_{01}^{1/2}}{\Lambda^3}H(\bar{D}Q)(\bar{\psi}\gamma_5\psi) + \frac{c_{02}^{1/2}}{\Lambda^3}H^\dagger(\bar{Q}D)(\bar{\psi}\psi) + \frac{\tilde{c}_{02}^{1/2}}{\Lambda^3}H^\dagger(\bar{Q}D)(\bar{\psi}\gamma_5\psi)$$

  - the resulting final state kaon momentum distributions will differ

J.F.K & C. Smith
2010



axial, vector, chiral couplings
m_ψ=0, 1, 2 GeV



similar conclusions for two scalars in
Altmannshofer et al., 0902.0160

Conclusions

- Rare B decays are sensitive probes of NP
  - generally correlations among observables (also $\Delta B=2$, charged currents)

starting to over-constrain even MFV NP

clear patterns in concrete models

Conclusions

- Rare B decays are sensitive probes of NP

  - generally correlations among observables (also $\Delta B=2$, charged currents)

    starting to over-constrain even MFV NP

    clear patterns in concrete models

  - $b \to s$ transitions will be crucial to help reconstruct the NP model responsible for new effects in B_s oscillations

    probing for new CPV sources & departures from (G)MFV assumptions

    - $\Delta F=2$ FCNC non-leptonic decays ($b \to ss\bar{d}$ and $b \to dd\bar{s}$)

Huitu et al., hep-ph/9809566
Fajfer & Singer., hep-ph/0007132
Fajfer, J.F.K. & Kosnik, hep-ph/0605260
Pirjol & Zupan, 0908.3150

Conclusions

- Rare B decays are sensitive probes of NP
  - generally correlations among observables (also $\Delta B=2$, charged currents)

    starting to over-constrain even MFV NP

    clear patterns in concrete models

  - $b \to s$ transitions will be crucial to help reconstruct the NP model responsible for new effects in B_s oscillations

    probing for new CPV sources & departures from (G)MFV assumptions

  - $b \to s/d\, E_{miss}$ can receive contributions from particles other than neutrinos in final state - modifications in spectra need to be accounted for in bounds

Backup Slides

New physics flavor problem

- SM as an effective low energy theory

  - EFT (higher dim. operators): $L_{SM} = L_{gauge} + \mu(\Lambda)^2 H^\dagger H - \lambda (H^\dagger H)^2 + L_{Yukawa}$

    Determines the EW scale

    SM Flavor & CPV

    $+ L_5/\Lambda + L_6/\Lambda^2 + \ldots$

    See-saw

    FCNC, CPV, etc…

  - EW hierarchy problem suggests: $\Lambda \leq 1$ TeV

  - ε_K, $b \to s\gamma$ bounds on generic NP operators: $\Lambda > 10^2 - 10^5$ TeV

Tension between these estimates of expected NP scales

The large tan β

- The large tan β scenario: Two EW Higgs doublets (H_u , H_d) – simplest (natural) extension of the SM Higgs sector, necessity in SUSY models.

- tan β = v_u /v_d MFV enables to separate breaking of $U(1)_{PQ}$ from that of $SU(3)_q^3$

    - $\epsilon_i \bar{Q}_L (Y_D Y_D^\dagger)^{n1} (Y_U Y_U^\dagger)^{n2} (Y_D Y_D^\dagger)^{n3} Y_D D_R (H_u)^c$,

    - $\epsilon_j \bar{Q}_L (Y_D Y_D^\dagger)^{n4} (Y_U Y_U^\dagger)^{n5} (Y_D Y_D^\dagger)^{n6} Y_U U_R (H_d)^c$,

- NP contributions proportional to the bottom Yukawa become important as $\lambda_b(\sim m_b \tan\beta/v_u) \sim \lambda_t$ (operator structure $D_R Y_D^\dagger Y_U Y_U^\dagger Q_L$)

- Partial lifting of helicity suppression in the down sector (charged and neutral Higgs exchange)