Flavour physics (3)

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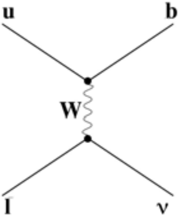
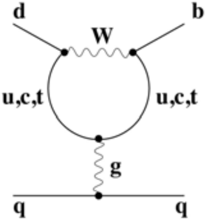
Outline

- Why and how flavour is useful
- Flavour in the Standard Model
- Hints of NP in flavour data
  - $\Delta F = 1$ Flavour Changing Charged Currents: Charged Higgs ? Right-handed currents ?
  - $\Delta F = 2$ Flavour Changing Neutral Currents: NP in boxes ?
  - $\Delta F = 1$ Flavour Changing Neutral Currents: NP in radiative penguins ?

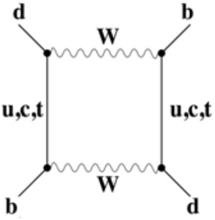
Processes of interest



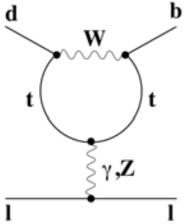
Semi/leptonic



Penguins



Mixing



Radiative

	Semi/leptonic	Penguins	Mixing	Radiative
Process	$\Delta F = 1$ FCCC	$\Delta F = 1$ FCCC	$\Delta F = 2$ FCNC	$\Delta F = 2$ FCNC
NP sensitiv.	Small	Large ?	Large	Large
B	$B \to D\ell\nu$, $B \to \tau\nu$	$B \to \pi\pi$	$\Delta m_d, \Delta m_s$	$B \to K^*\mu\mu, B_s \to \mu\mu$
D	$D \to K\ell\nu$, $D_s \to \mu\nu$	$D \to K\pi$	x, y, ϕ	$D \to X_u\ell\ell$
K	$K \to \pi\ell\nu$, $\tau \to K\nu$	$K \to \pi\pi$	ϵ_K	$K \to \pi\nu\nu, K \to \mu\mu$

The NP point of view: SM as an effective theory

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

At low energies, below the scale Λ of new particles

$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

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New operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Made of SM fields, compatible with its symmetries,
- Split high energies c_n and low energies O_n, separated by scale Λ

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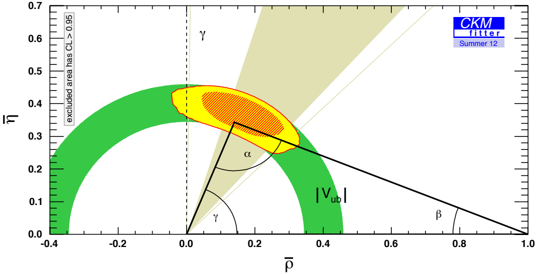
- New d.o.f. and energy scale of NP ? — High-p_T expts
- Symmetries and structure ? — Flavour expts

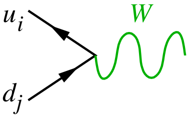
$\Delta F = 1$ FCCC

Charged Higgses ?

Right-handed currents ?

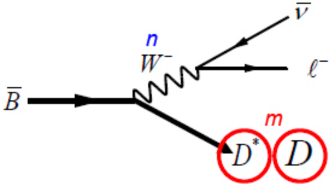
NP in $\Delta F = 1$ FCCC

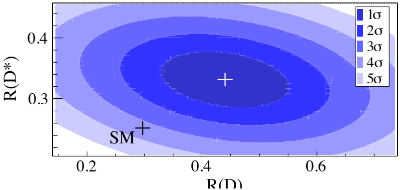




- Should be large to compete with tree-level SM contributions
- No obvious disagreement among these “clean” observables
- But some room for NP (γ, exclusive vs inclusive $|V_{xb}|$)

$B \to D(^*)\tau\nu$





$$\frac{d\Gamma(B\to D^*\tau\nu)}{dq^2} \propto \left[\left(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2\right)\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2}|H_{0t}|^2\right]$$

with H_{mn} helicity amplitude for (D^*, W) [for D, only H_{00} and H_{0t}]

$$\frac{\Gamma(\bar{B}\to D\tau\nu)}{\Gamma(\bar{B}\to D\ell\nu)} = 0.440 \pm 0.058 \pm 0.042 \text{ [Babar]}, \quad 0.430 \pm 0.091 \text{ [Belle]}, \quad 0.297 \pm 0.017 \text{ [SM]}$$

$$\frac{\Gamma(\bar{B}\to D^*\tau\nu)}{\Gamma(\bar{B}\to D^*\ell\nu)} = 0.332 \pm 0.024 \pm 0.018 \text{ [Babar]} \quad 0.405 \pm 0.047 \text{ [Belle]}, \quad 0.252 \pm 0.003 \text{ [SM]}$$

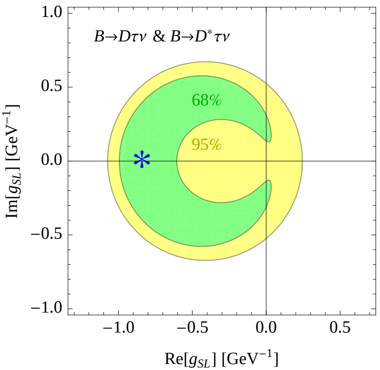
[Fajfer, Kamenik, Nizandzic]

SM prediction

- based on $B \to D(^*)$ form factors (4 for $B \to D^*$, 2 for $B \to D$)
- constrained by HQE, lattice ($B \to D$) and experiment ($B \to D^*$)

Effective approach

$$\frac{d\Gamma(B\to D^*\tau\nu)}{dq^2} \propto \left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_{0t}|^2\right]$$



Scalar contribution, seen only in helicity-suppressed $O(m_\tau^2)$?

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}}[\bar{c}\gamma^\mu P_L b + g_{SL} i\partial^\mu(\bar{c}P_L b)] \times \sum_{\ell=e,\mu,\tau} \bar{\ell}\gamma_\mu P_L \nu_\ell + h.c.$$

[Fajfer, Kamenik, Nizandzic]

$\Longrightarrow$Natural interpretation in terms of charged Higgs contribution

Two-Higgs doublet models

- Different two-Higgs doublet models (2HDM) with ϕ_1 and ϕ_2
  - type I : ϕ_1 coupling to both up- and down-type, ϕ_2 to none
  - type II : ϕ_1 coupling to up-type, ϕ_2 to down-type (and leptons)
  - type III : ϕ_1 and ϕ_2 coupling both to both types of quarks

  with EWSB $\langle 0|\phi_1|0\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}$ and $\langle 0|\phi_2|0\rangle = \begin{pmatrix} v_2/\sqrt{2} \\ 0 \end{pmatrix}$

- Higgs: 2 charged, 2 neutral scalar, one neutral pseudoscalar

- For instance, 2HDM(II) looks like SM with Yukawa matrices $Y^{D,U,E}$

$$\mathcal{L}_{II} = -\bar{Q}_L \phi_1 Y^d d_R - \bar{Q}_L \phi_2 Y^u u_R - \bar{E}_L \phi_2 Y^e e_R + h.c.$$

(SM would be $\phi_2 = i\sigma_2 \phi_1^*$)

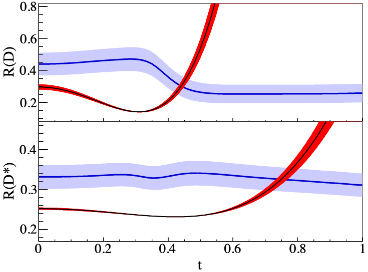
- Extension of 2HMD with Z_2-symmetry (I,II,X, Y) to aligned models

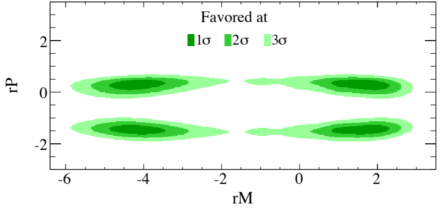
$$\mathcal{L}_A = -\bar{Q}_L(\phi_1\Gamma_1+\phi_2\Gamma_2)d_R-\bar{Q}_L(\phi_1\Delta_1+\phi_2\Delta_2)u_R-\bar{E}_L(\phi_1\Pi_1+\phi_2\Pi_2)e_R+h.c.$$

with proportionality between Γ_1 and Γ_2, Δ_1 et Δ_2, Π_1 and Π_2

avoiding FCNC at tree level [Pich, Tuzón]

Which 2HDM ?



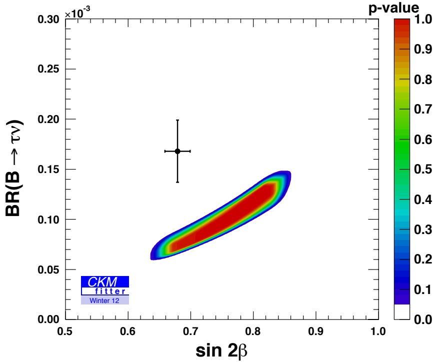


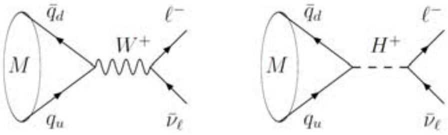
2HDM II ($t = \tan\beta/m_{H^+}$) 2HDM III

- not compatible with the most usual 2HDM of type II [Babar]
- not compatible with “aligned” extension [Celis, Jung, Li, Pich]
- compatible with 2HDM model of type III [Babar; Crivellin, Greub, Kokulu]
- more observables, sensitive to scalar: D^* polarisation, τ helicity

- relies on scalar form factors and validity of HQE
- e.g., lattice-inspired $B \to D\tau\nu$ FFs increases SM prediction: $0.297 \pm 0.017 \to 0.31 \pm 0.02$ [Becirevic, Kosnik, Tayduganov]

Looking for confirmation: $B \to \tau\nu$



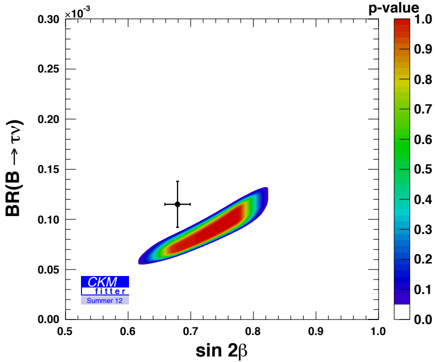


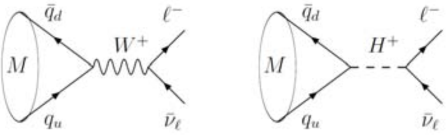
- Up to Winter 2012, discrepancy in SM for $B \to \tau\nu$ vs $\sin(2\beta)$:

  2.8σ [Moriond 12]
- Often interpreted in terms of charged Higgs exchange

$$Br(B \to \tau\nu_\tau)_{2HDMII} = Br_{SM}(1 - \tan^2\beta \times m_B^2/m_{H^+}^2)^2$$

Failing to confirm: $B \to \tau\nu$





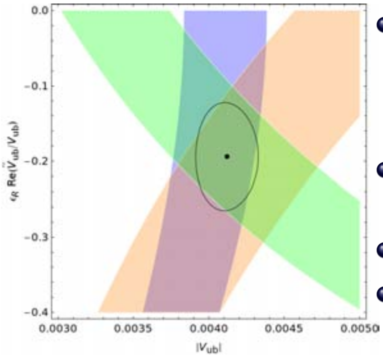
- *Used to* have significant discrepancy in SM for $B \to \tau\nu$ vs $\sin(2\beta)$

  2.8σ [Moriond 12] $\to$ 1.6σ [ICHEP 12]
- Reduction in 2012 due to new Belle result changing WA
- Brings CKM-independent $d\Gamma(B \to \pi\ell\nu)/dq^2/Br(B \to \tau\nu)$ closer to non-perturbative estimates (sum rules, lattice) [A. Khodjamirian et al.]

Right-handed currents

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

for instance through W_R from $SU_C(3) \otimes SU_L(2) \otimes SU_R(2) \otimes U_Y(1)$, broken at a heavy scale of a few TeV into the SM group

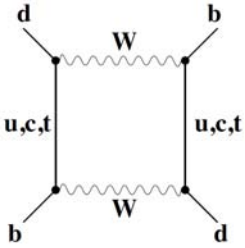


- V and $\tilde{V}$ unitary, $\epsilon_{L,R} \ll 1$
- useful for $|V_{ub}|$ to agree between
  - $B \to \tau\nu_\tau$ ($\gamma_\mu\gamma_5$ B-coupling, orange)
  - $B \to \pi\ell\nu_\ell$ (γ_μ B-coupling, green)
  - $B \to X_u\ell\nu_\ell$ (mixture, blue)
- does not solve problem of $Br(B \to D^{(*)}\tau\nu_\tau)/Br(B \to D^{(*)}\ell\nu_\ell)$
- no hint from $b \to s\gamma^{(*)}$ (see later)
- explicit models involve additional H^0 generating tree-level $\Delta F = 2$

[Buras, Gemmler, Isidori, Blanke, Heidsieck]

$\Delta F = 2$ FCNC
New particles in the box ?

NP in neutral-meson mixing ?



In SM, $B_d\bar{B}_d$ dominated by top boxes

$$\phi_{B_d} = arg([V_{tb}V_{td}^*]^2) = 2\beta$$

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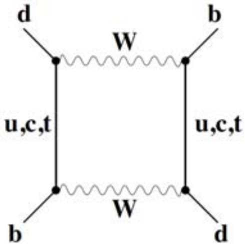

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Adding contribution from higher-order operators, including LO $(\bar{b}_L\gamma_\mu d_L)^2$

$$A_{\Delta B=2} \propto \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2}\langle\bar{B}|(\bar{b}_L\gamma_\mu d_L)^2|B\rangle$$

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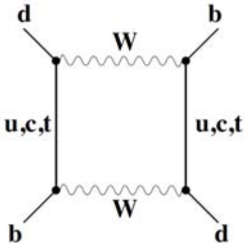

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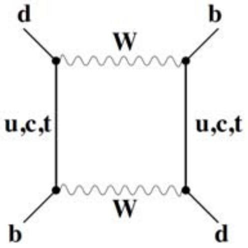

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We can get an upper bound on Λ by

- Combining information from B and K mixing
- Assuming a typical size for c_{NP}
- Getting how much th. and exp. uncertainties leave room for NP

$\Delta F = 2$ FCNC constraints

Operator	Bounds on Λ in TeV ($c_n = 1$) Re	Im	Bounds on c_n ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
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[Isidori, Nir, Perez 2010]

Neutral meson mixing ($\Delta F = 2$) SM-like, and c_i/Λ^2 must be small:

- Significant mass gap
- Couplings with close-to-SM pattern of flavour violation
- Additional selection rules

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[Isidori, Nir, Perez 2010]

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NP flavour problem: BSM models with many flavour violation sources

- Decoupling *[Λ large compard to Λ_{EW}, loop suppression]*
- Universality *[Minimal Flavour Violation: all flavour viol. from Yukawa]*
- Alignment *[Loops with NP only, diagonal in flavour basis]*

Minimal Flavour Violation (1)

Remain as close as possible to SM pattern of flavour breaking

- Very large flavour group of the SM gauge sector
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
- Broken only by quark Yukawa couplings Y_U and Y_D
- Responsible for suppression of FCNC, pattern of CP violation

Write extensions of the SM with Minimal Flavour Violation

- Promoting global flavour symmetry as “exact”
- Introducing Y_D and Y_U as v.e.v of auxiliary fields
- Write operators invariant under this symmetry

$$\mathcal{L} = \bar{Q}_L^i Y_D^{ik} d_R^k \phi + \bar{Q}_L^i Y_U^{ik} u_R^k \phi_c + h.c.$$

	$SU(3)_{Q_L}$	$SU(3)_{u_R}$	$SU(3)_{d_R}$
Q_L	3	1	1
u_R	1	3	1
d_R	1	1	3
Y_D	3	1	$\bar{3}$
Y_U	3	$\bar{3}$	1

Minimal Flavour Violation (2)

- Example of dim-6 MFV operator: $[\bar{Q}_L^i (Y_U Y_U^\dagger) Q_L^j]] \times \bar{E}_L E_L$

$$Y_D = (y_d, y_s, y_b), \qquad Y_U = V^\dagger (y_u, y_c, y_t) \qquad (Y_U Y_U^\dagger)_{ij} \simeq y_t^2 V_{3i}^* V_{3j}$$

- Same CKM structure as SM for flavour-changing loop processes
- Only flavour-independent magnitude change wr.t. SM, thus hidden in hadronic uncertainties and cancel in ratios like

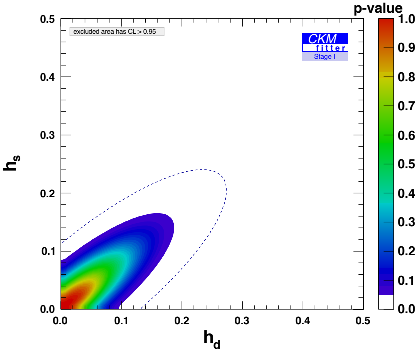
$$(\Delta m_d / \Delta m_s)_{MFV} = (\Delta m_d / \Delta m_s)_{SM}$$

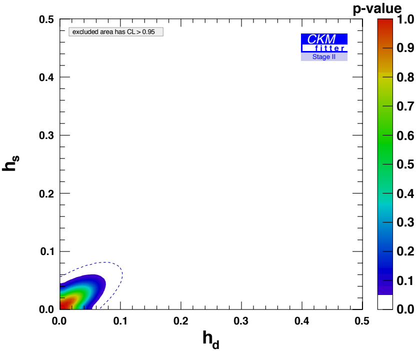
- Reduces bounds on the scale of NP down to a few TeV

- Not a theory of flavour (no explanation on structure of Yukawas and why only source of flavour breaking)
- Plausible, but not verified (no unambigouous deviations from SM in flavour-independent part)

$\Delta F = 2$ FCNC constraints in the future

- Stage I: $7\,\mathrm{fb}^{-1}$ LHCb data + $5\,\mathrm{ab}^{-1}$ Belle II + lattice improv.
- Stage II: $50\,\mathrm{fb}^{-1}$ LHCb data + $50\,\mathrm{ab}^{-1}$ Belle II + lattice improv.





NP in B_d and B_s mixings

$$M_{12}^q = (M_{12}^q)_{\rm SM} \times \left(1 + h_q\, e^{2i\sigma_q}\right)$$

from $C_{ij}/\Lambda^2 \times (\bar{b}_L \gamma^\mu q_L)^2$

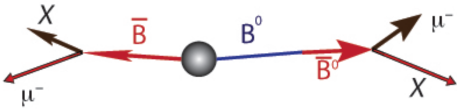
[J. Charles et al.]

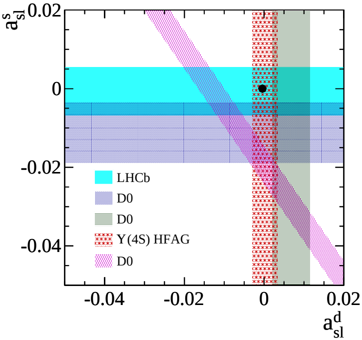
Couplings (Stage II)	NP loop order	Scales (in TeV) probed by B_d mixing	B_s mixing
$\|C_{ij}\| = \|V_{ti} V_{tj}^*\|$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\|C_{ij}\| = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

Dimuon asymmetry

CP-violation in mixing through comparison of wrong-sign decays $(\ell^- \leftarrow \bar{B}(b\bar{q}) \leftrightarrow B(\bar{b}q) \rightarrow \ell^+)$

$$a_{SL}^q = \frac{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)-\Gamma(B_q(t)\to\ell^-\nu X)}{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)+\Gamma(B_q(t)\to\ell^-\nu X)}$$





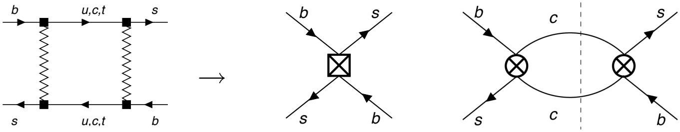
- Same-sign dimuon charge asym. $A_{SL} = (-0.85 \pm 0.28)\%$ [CDF, DØ] linear combination of a_{SL}^d and a_{SL}^s, disagrees with SM at 3 σ
  $$A_{SL}^{SM} = -(0.020 \pm 0.003)\%$$ [Lenz,Nierste]
- Individual semileptonic asyms. from $B_q \to D_q \mu X$ OK with SM
  $$a_{SL}^d = (0.38 \pm 0.36)\%$$ [B-factories, Tevatron]
  $$a_{SL}^s = (-0.22 \pm 0.52)\%$$ [DØ, LHCb]

Evolution of the B_q system

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(M^q - \frac{i}{2}\Gamma^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

- Non-hermitian Hamiltonian (only 2 states) but M and Γ hermitian
- Mixing due to non-diagonal terms $M_{12}^q - i\Gamma_{12}^q/2$

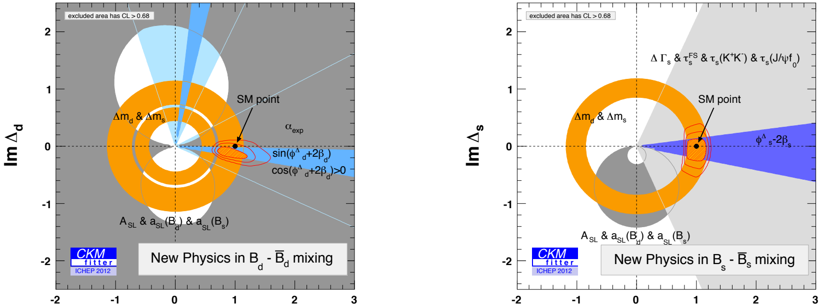
Eff. Hamiltonian integrating out heavy W, Z, t



- M_{12}^q dominated by dispersive part of top boxes [Re[loops]]
  - related to heavy virtual states ($t\bar{t}\ldots$)
- Γ_{12}^q dominated by absorptive part of charm boxes [Im[loops]]
  - common B and $\bar{B}$ decay channels into final states with $c\bar{c}$ pair
  - non local contribution, computed assuming quark-hadron duality and expanded in $1/m_b$ and α_s series of local operators

New Physics in M_{12}

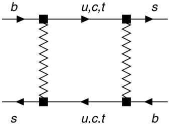
- M_{12} dominated by (virtual) top boxes
  [affected by NP, e.g., if heavy new particles in the box]
- Γ_{12} dominated by tree decays into (real) charm states
  [affected by NP if changes in (constrained) tree-level decays]
- Assume NP in $\Delta F = 2$ only via $M_{12}^q = (M_{12}^q)_{SM}\Delta_q$, affecting all observables describing B_d and B_s mixings
- Hard to accomodate non-SM A_{SL} with SM $\Delta m_{d,s}$, $\Delta\Gamma_s$.

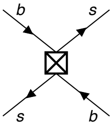


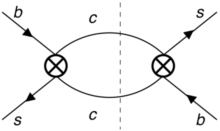
New physics also in Γ_{12}^s ?

$$\Delta M_s = 2|M_{12}^s| \qquad \Delta\Gamma_s = 2|\Gamma_{12}^s|\cos(\phi_s) \qquad a_{SL}^s = \frac{\Gamma_{12}^s}{M_{12}^s}\sin(\phi_s)$$

Could solve A_{SL}, but significant deviation of $\Delta\Gamma_s$ w.r.t. SM







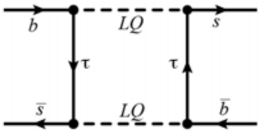
$$A_{\Delta B=2} = \langle \bar{B}|\mathcal{H}_{\rm eff}^{\Delta B=2}|B\rangle - \frac{1}{2}\int d^4x d^4y \langle \bar{B}|T\mathcal{H}_{\rm eff}^{\Delta B=1}(x)\mathcal{H}_{\rm eff}^{\Delta B=1}(y)|B\rangle$$

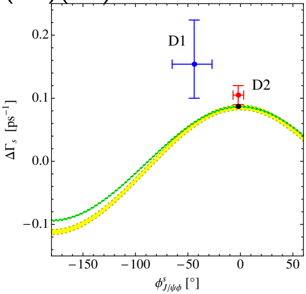
- Change in $b \to c\bar{c}s$ modes or new decay mode competing in Γ_{12}^s would affect Γ_s^{11} and thus Γ_s (in good agreement with SM)
- Change in $b \to c\bar{c}s$ modes affects also $B_d \to J/\psi K_s$ and $B_s \to J/\psi\phi$ and thus determination of B_d, B_s mixing angles
- Change in Γ_{12}^s impacts M_{12}^s (same box diagams with same particles) and thus ΔM_s (in good agreement with SM)

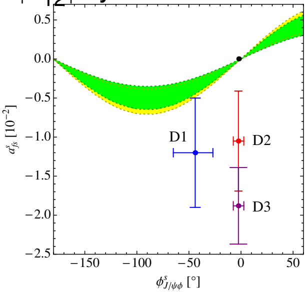
Maybe, but no model-independent way of connecting $\Gamma_{12}^s, \Gamma_{11}^s, M_{12}^s$

Specific model of New Physics in Γ_{12}^s

- $\tau\bar{\tau}$ intermediate states due to NP $(\bar{b}s)(\bar{\tau}\tau)$ operators ?
- Eff. Hamiltonian analysis of $b \to s\gamma$, $b \to s\ell^+\ell^-$, $b \to s\gamma\gamma$: room for scalar or vector $(\bar{b}s)(\bar{\tau}\tau)$ able to enhance $|\Gamma_{12}^s|$ by 30-40%



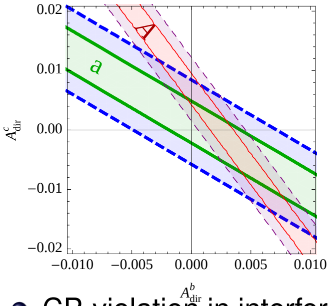




- But M_{12}^s and Γ_{12}^s correlated in specific models (e.g., $SU(2)$ singlet scalar leptoquark) making it difficult to accomodate all data ($\sim D2$)
- General problem for $(M_{12}^s)_{NP}/(\Gamma_{12}^s)_{NP}$ real, linking ΔM_s, $\Delta\Gamma_s$, a_{SL}^s [weakest ΔM_s constraint if light NP scale or GIM-like mechanism]

[Haisch, Bobeth]

Other explanations



- Direct CP-violation in muonic semileptonic b or c decays
  - Requires inclusive asymmetries $A^c_{\rm dir} = O(1\%)$ or $A^b_{\rm dir} = O(0.3\%)$
  - Experimentally possible, but realistic models genrarting such asymmetry ?

[Gronau et al.; SDG, Kamenik]

- CP-violation in interference for $B_d \to c\bar{c}d\bar{d}$
  - Contribution to the dimuon asymmetry proportional to $\sin(2\beta)$

$$p\bar{p} \to B^+\bar{B}^0X,\ B^+ \to \mu^+X,\ \bar{B}^0 \to D^+D^-, D^+ \to \mu^+Y$$

$$p\bar{p} \to B^-B^0X,\ B^- \to \mu^-X,\ B^0 \to D^+D^-, D^- \to \mu^-Y$$

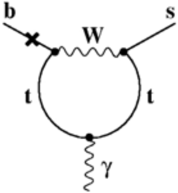
  - interference due to evolution of B^0 or $\bar{B}^0$ before decaying into D^+D^-
  - which could explain a good part of the effect on A_{SL}
  - not taken into account in the current DØ analysis

[Borissov, Hoeneisen]

$\Delta F = 1$ FCNC
Z' boson

Effective Hamiltonian for radiative decays

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} C_i Q_i + \ldots$$



- $Q_7 = \frac{e}{g^2} m_b \, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ [real or soft photon]
- $Q_9 = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\ell$ [$b \to s\mu\mu$ via Z/hard γ]
- $Q_{10} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b \, \bar{\ell}\gamma_\mu\gamma_5\ell$ [$b \to s\mu\mu$ via Z]

NP changes short-distance C_i (including new phases)
and/or add new long-distance ops Q'_i

- Chirally flipped operators ($W \to W_R$)
  $Q_7 \propto \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b \to Q_{7'} \propto \bar{s}\sigma^{\mu\nu}(1-\gamma_5)F_{\mu\nu}\, b$
- Scalar/pseudoscalar operators ($\gamma \to H$)
  $Q_9 \propto \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma_\mu\ell \to Q_S \propto \bar{s}b(1+\gamma_5)\bar{\ell}\ell$, $Q_P \propto \bar{s}b(1+\gamma_5)\bar{\ell}\gamma_5\ell$
- Tensor operators ($\gamma \to T$)
  $Q_9 \propto \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{\ell}\gamma_\mu\ell \to Q_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\,\bar{\ell}\sigma_{\mu\nu}\ell$

Processes of interest

	$B \to (X_s, K^*)\gamma$	$B \to (X_s, K, K^*)\ell^+\ell^-$	$B_s \to \ell^+\ell^-$
$C_7, C_{7'}$	$\times$	$\times$	
$C_9, C_{9'}$		$\times$	
$C_{10}, C_{10'}$		$\times$	$\times$
$C_S, C_{S'}, C_P, C_{P'}$		$\times$	$\times$
$C_T, C_{T'}$		$\times$	

Hadronic inputs

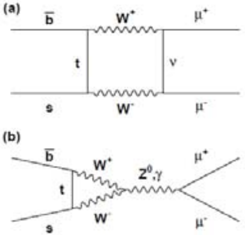
- $B_s \to \mu\mu$: decay constant (lattice)
- Exclusive $B \to K(^*)$: form factors (lattice, light-cone sum rules)
- Inclusive $B \to X_s$: OPE matrix elements (fit combined with $B \to X_c\ell\nu$)

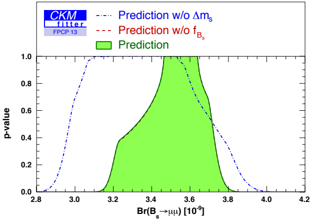
Once short-distance C_i determined,
it remains to find the appropriate underlying model

$B_s \to \mu\mu$: the framework

$$Br(B_s \to \mu^+\mu^-) = \tau_{B_s} \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2\theta_W}\right)^2 f_{B_s}^2 m_{B_s}^3 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2$$

$$\times \left[\frac{m_{B_s}^2}{m_b^2} |C_S - C_{S'}|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + \left| \frac{m_{B_s}}{m_b}(C_P - C_{P'}) + 2\frac{m_\mu}{m_{B_s}}(C_{10} - C_{10'}) \right|^2 \right]$$





$$Br(B_s \to \mu^+\mu^-)_{SM} = \tau_{B_s} \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2\theta_W}\right)^2 f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 \eta_Y^2 Y^2(m_t/M_W)$$

- LHCb+CMS: $Br(B_s \to \mu\mu)_{\rm exp} = (2.9 \pm 0.7) \cdot 10^{-9}$ ($> 5\sigma$)
- NLO pred from global fit: $Br(B_s \to \mu\mu)_{\rm SM,th} = (3.55^{+0.18}_{-0.34}) \cdot 10^{-9}$

$B_s \to \mu\mu$: predicting the branching ratio

- Comparing theoretical and experimental predictions
  - Theoretically: CP-average at fixed $t = 0$
  - Experimentally: CP-average integrated over t (including B_s mixing)

[SDG, Matias, Virto, De Bruyn, Fleischer, Knegiens,Koppenburg, Merk, Pellegrino, Tuning]

$$Br(B_s \to f)_{th} = \frac{1 - y_s^2}{1 + A^f_{\Delta\Gamma} y_s} Br(B_s \to f)_{exp,untag} \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

$$\Gamma(B_s(t) \to f) + \Gamma(\bar{B}_s(t) \to f) = e^{-\Gamma_H t/2}(1 + A^f_{\Delta\Gamma}) + e^{-\Gamma_L t/2}(1 - A^f_{\Delta\Gamma})$$

In SM: $A^{\mu\mu}_{\Delta\Gamma} = 1, Br(B_s \to \mu\mu)_{t=0} \simeq 0.91 \cdot Br(B_s \to \mu\mu)_{\text{time integrated}}$

[De Bruyn, Fleischer, Knegiens,Koppenburg, Merk, Pellegrino, Tuning]

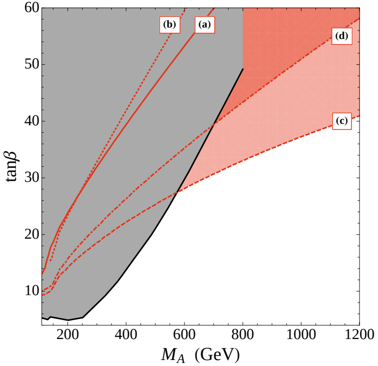
- Choice of inputs and higher orders
  - $Br \propto m_t^3$ via the short-distance Wilson coefficient
  - $m_t^{\bar{MS}}$ from m_t^{pole} (“measured”), but at which order (NLO or N^{3}LO ?)
  - SM prediction with NNLO strong and NLO weak corrections:

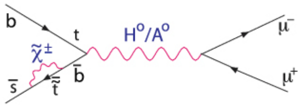
$$Br(B_s \to \mu\mu)_{\text{SM,th,time integrated}} = (3.65 \pm 0.23)10^{-9}$$

[Bobeth,Gorbahn,Hermann,Misiak,Stamou,Steinhauser]

Constraints on models

- Model independent approach: pattern of cancellation between $C_{10}, C_{10'}, C_P, C_{P'}$ to mimic $|C_{10}^{SM}|$, and $C_P \simeq C_{P'}$
- Particularly stringent constraint for susy models (and 2HDM models), especially at large $\tan\beta$





$\propto \frac{\tan\beta^3}{m_A^2}$

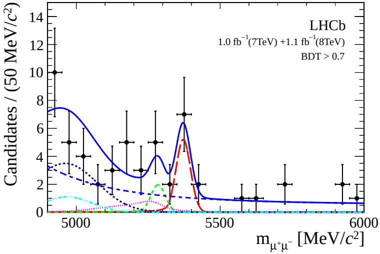
- grey: direct searches $H, A \to \tau\tau$
- red: $B_s \to \mu\mu$ constraint for different benchmark points

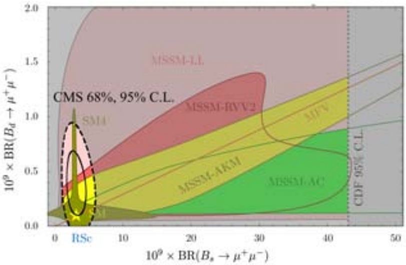
[Altmannshofer et al]

$B_s \to \mu\mu$ versus $B_d \to \mu\mu$

Combination of LHCb and CMS measurements

- $Br(B_s^0 \to \mu^+\mu^-)_{\rm exp} = (2.9 \pm 0.7) \times 10^{-9}$ (at more than 5 σ)
- $Br(B_d^0 \to \mu^+\mu^-)_{\rm exp} = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$ (at less than 3 σ)





[Kamenik, updated of Straub]

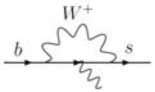
- $Br(B_d^0 \to \mu\mu)_{\rm SM,th,time\ integrated} = (1.06 \pm 0.09)10^{-10}$, below exp ?
- Sensitive to FCNC scalar currents and electroweak penguins
- Stringent constraint on models in the future,

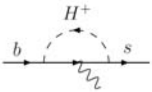
  especially non-MFV couplings for *bd* and *bs* FCNC

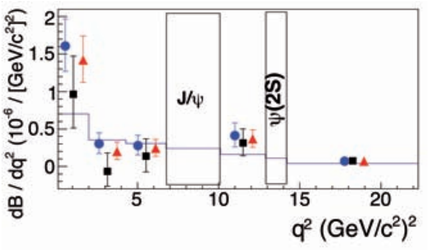
Inclusive radiative

$B \to X_s \gamma$

- Exp aver: $Br(B \to X_s\gamma)_{E_\gamma > 1.6 \text{ GeV}} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$
- NNLO SM prediction $Br = (3.13 \pm 0.22) \times 10^{-4}$ [Misiak,Steinhauser]
- Strong constraint on NP, in particular for models with H^+f



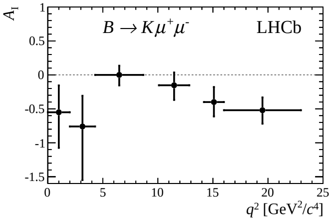


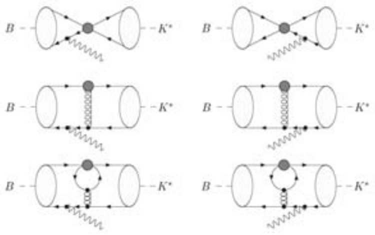


$B \to X_s \ell\ell$

- Branching ratios for $\ell = e, \mu$, recent binned results by Babar
- NNLO SM prediction at low and high q^2 [Huber, Lunghi, Misiak,Wyler, Hurth]
- Weak constraint on NP, due to large number of operators involved

Isospin asymmetry in $B \to K\ell^+\ell^-$



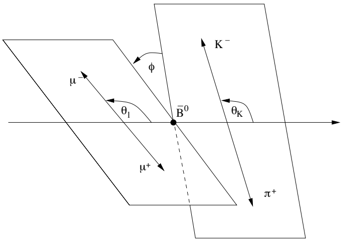


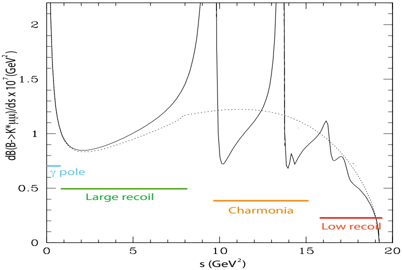
- Integrated over q^2: 4.4 σ from 0 (but nothing for $B \to K^*\mu^+\mu^-$)
- Purely spectator quark effect
- Requires calculation of $1/m_b$-suppressed corrections in QCD factorisation (weak annihilation, quark-loop spectator scattering)
- In SM, small non-local effects/soft-gluon diagrams, with a prediction below 1.5% (but with large uncertainties)
- No clue of which NP could produce such an effect...

Hard to break isospin for K and not K^* !

[Kagan, Neubert, Feldmann, Matias, Khodjamiran, Mannel, Yang, Lyon, Zwicky. . .]

$B \to K^* \ell\ell$



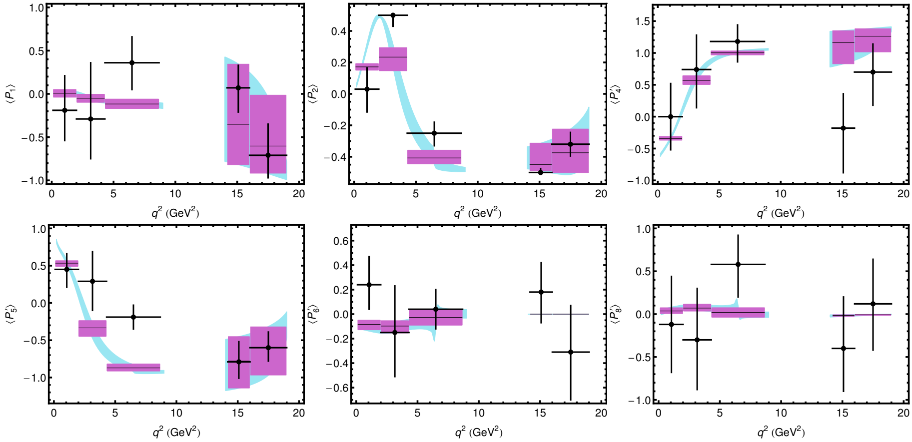


- Angular analysis yields $\mathrm{Re}[AB^*]$, $\mathrm{Im}[AB^*]$ between 8 amplitudes A

$$A = V_{tb} V_{ts}^* \sum C_i \times \text{form factors} \times \text{kinematic factors}$$

  - $B \to K^* V^* (\to \ell\ell)$ with given helicities for K^* and V^*, chirality of $\ell\ell$
  - depending on $q^2 = s$ invariant mass of the lepton pair
- Optimized observables in terms of angular coefficients
  - Relations among form factors in effective theories for large- or low-recoil of the K^* meson
  - Ratios of angular coefficients with controlled hadronic uncertainties in these two kinematic regimes

$B \to K^* \ell\ell$ angular observables

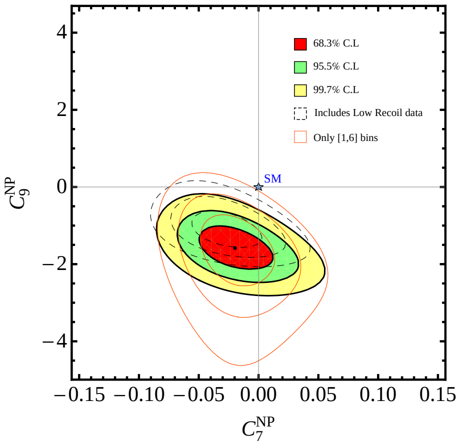


[LHCb; SDG, Matias, Virto]

Meaning of the discrepancy in P_2 and P_5'
between data (crosses) and SM predictions (purple) ?

Global fit to radiative decays

Standard χ^2 frequentist analysis (asymmetric errors combined in quadrature but no experimental correlations) [SDG, J.Matias, J.Virto]



$$C_i = C_i^{SM} + C_i^{NP}$$

- $B \to K^*\mu\mu$: $P_1, P_2, P_4', P_5', P_6', P_8', A_{FB}$
- $B \to X_s\gamma$: Br
- $B \to X_s\mu^+\mu^-$: Br
- $B_s \to \mu\mu$: Br
- $B \to K^*\gamma$: A_I and $S_{K^*\gamma}$

Several sets of data of $B \to K^*\mu\mu$ [LHCb only]

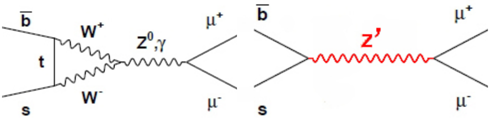
- full: 3 fine large-recoil bins
- dashed: 3 fine large-recoil bins + low-recoil bins
- orange: 1 large recoil-bin only

Model building

Need for C_9^{NP} confirmed by

- Alternative analysis with different angular observables and binning
- Lattice analysis of $B \to K^*\ell\ell$ and $B_s \to \phi\ell\ell$ large-recoil Br

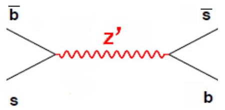
[W. Altmannshofer, D. Straub; Horgan et al.]]

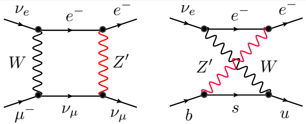


Which model for this pattern ?

- Contribution to (real) C_9: FCNC coupling b and $s \propto V_{ts}^* V_{tb}$
- No (or small) contribution to $C_{S,P}$: vector meson (Z' style)
- No (or small) contribution to $C_{9'}$: coupling to left-handed b and s
- No (or small) contribution to $C_{10(')}$: vector coupling to muons

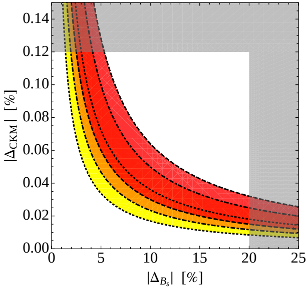
Z' boson: the simplest version





Such a Z' would also affect at least

- $B_s\bar{B}_s$ mixing $[\Delta_{B_s} = \Delta m_s/\Delta m_s^{SM} - 1]$
- G_F, leading to unitarity violation in 1st row of V_{CKM} $[\Delta_{CKM} = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2]$
- $b \to s\nu\bar{\nu}$ [still to be observed...]



Correlation between deviations (depend on $M_{Z'}$ =1,3,10 TeV) OK within current bounds

[R. Gauld, F. Goertz, U. Haisch]

Z' boson: more evolved versions

Left-handed scenario

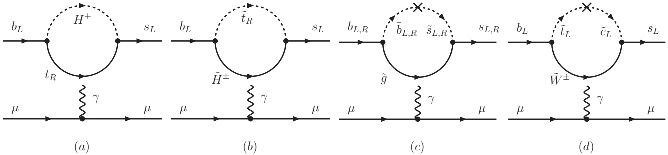
- Z' FCNC coupling only to left-handed down-type quarks
- large contrib to C_9 requires Δm_d and Δm_s enhanced w.r.t. SM
- ...requiring lower values of bag parameters to agree with data

3-3-1 models

- $SU_C(3) \otimes SU_L(3) \otimes U_X(1)$ broken above EW scale
- No anomaly: 3 generations, different representations for 1st-2nd and 3rd generations (justification for large m_t ?)
- $Q = T_3 + \beta T_8 + X$ with $|\beta| \leq \sqrt{3}$
- Additional gauge bosons, in particular neutral Z' with tree-level FCNC (strong correlations for NP in radiative C_i)
- $\beta = -\sqrt{3}$ with $M_{Z'} = O(7\text{ TeV})$ agree with most constraints
- ...but problems of internal consistency for $M_{Z'} > 4$ TeV and potentially large deviations in $\Delta m_d, \Delta m_s$

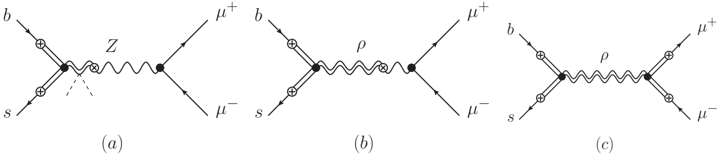
[R. Gauld, F. Goertz, U. Haisch, A. Buras, J. Girrbach, D.Straub, W.Altmanshoffer]

Alternative models



MSSM

- Easy to generate contributions to $C_7, C_{7'}$
- Difficult to shift C_9 (and $C_{9'}$) significantly from SM value



Composite models

- Mixing of light d.o.f. with composite heavy partners
- Similar problems as MSSM: OK for dipole operators, but not $C_{9,9'}$
- Maybe large compositeness for one muon chirality, but $C_{10,10'}$?

[D.Straub, W.Altmanshoffer; F. Mahmoudi, S. Neshatpour, J. Virto]

Outlook

Outlook

Flavour physics

- Low-energy window on electroweak scale and beyond
- Using SM symmetries to look for tell-tale signs of NP
- Exploiting different scales through a series of effective theories
- Long distances: non-perturbative QCD source of uncertainties
- Overall agreement with CKM pattern embedded in SM
- Interesting deviations: can we check them/understand them ?

Two approaches to analyse flavour physics observables

- Model-independent: focus on class of quark processes to constrain c/Λ^2 and operator structure
- Model-dependent: design model and connect it with other flavour constraints (and high-p_T if possible)

Powerful tool to probe and constrain not only SM but also NP
if enough data from different sources to extract meaningful patterns
(more from LHCb, but also CMS, ATLAS, NA62...)