Flavour physics
A new song to an old tune

Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS & Université Paris-Sud 11, 91405 Orsay, France

Babar collaboration meeting, LAPP
June 28 2011

Foreword

Remarkable achievement in flavour physics over the last decades

- Extensive experimental programmes B-factories
- Improvement in theoretical undestanding of strong interactions
- Confirming the validity of Kobayashi-Maskawa mechanism of CP-violation to a high accuracy

Flavour physics very good at mapping the structure of New Physics

- neutral meson mixings hinted at charm and top quarks
- CKM and hierachy of quark masses low-energy probe of Higgs-fermion interactions
- among most stringent constraints for any extension of SM ($K\bar{K}$ mixing, $b \to s\gamma \ldots$)

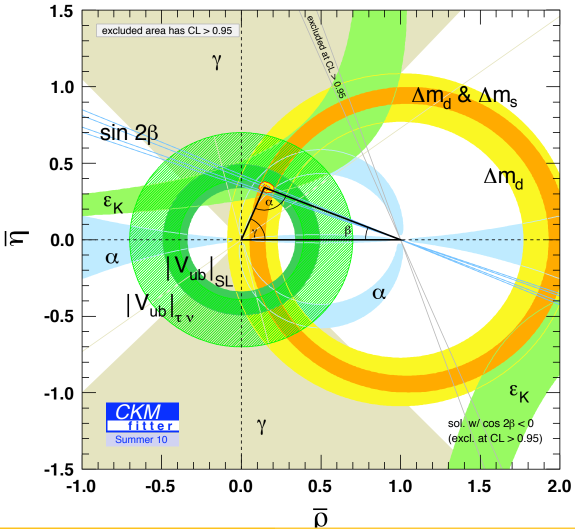
More and more, bottom-up exploration of NP using well-known quantities to constrain/imagine new models

Contents

Flavour physics from SM to NP

Unitarity triangle in the SM

Combining observables with good experimental and theoretical control



$|V_{ud}|$, $|V_{us}|$

$|V_{cb}|$, $|V_{ub}|_{SL}$

$B \to \tau\nu$

Δm_d, Δm_s

ϵ_K

$\sin 2\beta$

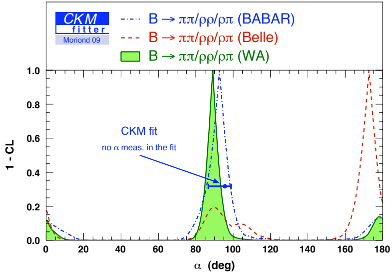
α

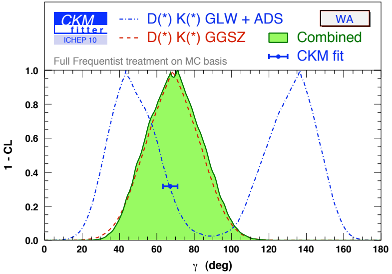
γ

$$A = 0.815^{+0.011}_{-0.029}$$
$$\lambda = 0.2254^{+0.0008}_{-0.0008}$$
$$\bar{\rho} = 0.144^{+0.029}_{-0.018}$$
$$\bar{\eta} = 0.342^{+0.016}_{-0.016}$$

(68% CL)

The three angles





- Two angles precisely measured: α (5%) and β (4.2%)
- Only γ less acurately measured (25%) than predicted (6%)

One of the many successes from the B factories

Making predictions in the Standard Model. . .

Observable	Measurement	Prediction	Pull (σ)
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	$(16.8 \pm 3.1) \cdot 10^{-5}$	$(7.57 {}^{+0.98}_{-0.61}) \cdot 10^{-5}$	2.8
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	$< 10^{-6}$	$(3.74 {}^{+0.44}_{-0.38}) \cdot 10^{-7}$	-
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	$(5.29 \pm 0.28) \cdot 10^{-2}$	$(5.44 {}^{+0.05}_{-0.17}) \cdot 10^{-2}$	0.5
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$	$(5.90 \pm 0.33) \cdot 10^{-3}$	$(5.39 {}^{+0.21}_{-0.22}) \cdot 10^{-3}$	1.3
$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$	$(3.82 \pm 0.32 \pm 0.09) \cdot 10^{-4}$	$(4.18 {}^{+0.13}_{-0.20}) \cdot 10^{-4}$	0.6
$\mathcal{B}(B_s^0 \to \tau^+\tau^-)$	-	$(7.73 {}^{+0.37}_{-0.65}) \cdot 10^{-7}$	-
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$< 32 \cdot 10^{-9}$	$(3.64 {}^{+0.17}_{-0.31}) \cdot 10^{-9}$	-
$\mathcal{B}(B_s^0 \to e^+e^-)$	$< 2.8 \cdot 10^{-7}$	$(8.54 {}^{+0.40}_{-0.72}) \cdot 10^{-14}$	-
$\mathcal{B}(B_d^0 \to \tau^+\tau^-)$	$< 4.1 \cdot 10^{-3}$	$(2.36 {}^{+0.12}_{-0.21}) \cdot 10^{-8}$	-
$\mathcal{B}(B_d^0 \to \mu^+\mu^-)$	$< 6 \cdot 10^{-9}$	$(1.13 {}^{+0.06}_{-0.11}) \cdot 10^{-10}$	-
$\mathcal{B}(B_d^0 \to e^+e^-)$	$< 8.3 \cdot 10^{-9}$	$(2.64 {}^{+0.13}_{-0.24}) \cdot 10^{-15}$	-
$\Delta\Gamma_s/\Gamma_s$	$0.092^{+0.051}_{-0.054}$	$0.179 {}^{+0.067}_{-0.071}$	0.5
$a^d_{\rm SL}$	$(-47 \pm 46) \cdot 10^{-4}$	$(\text{-}6.5 {}^{+1.9}_{-1.7}) \cdot 10^{-4}$	0.8
$a^s_{\rm SL}$	$(-17 \pm 91^{+12}_{-23}) \cdot 10^{-4}$	$(0.29 {}^{+0.09}_{-0.08}) \cdot 10^{-4}$	0.2
$a^s_{\rm SL} - a^d_{\rm SL}$	-	$(6.8 {}^{+1.9}_{-1.7}) \cdot 10^{-4}$	-
$\sin(2\beta)$	0.678 ± 0.020	$0.832 {}^{+0.013}_{-0.033}$	2.7
$\mathcal{B}(B_d \to K^*(892)\gamma)$	$(43.3 \pm 1.8) \cdot 10^{-6}$	$(64 {}^{+22}_{-21}) \cdot 10^{-6}$	1.2
$\mathcal{B}(B^- \to K^{*-}(892)\gamma) \cdot 10^6$	$(42.1 \pm 1.5) \cdot 10^{-6}$	$(66 {}^{+21}_{-20}) \cdot 10^{-6}$	1.1
$\mathcal{B}(B_s \to \phi\gamma)$	$(57^{+21}_{-18}) \cdot 10^{-6}$	$(65 {}^{+31}_{-24}) \cdot 10^{-6}$	0.1
$\mathcal{B}(B \to X_s\gamma)/\mathcal{B}(B \to X_c\ell\nu)$	$(3.346 \pm 0.247) \cdot 10^{-3}$	$(3.03 {}^{+0.34}_{-0.32}) \cdot 10^{-3}$	0.2
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$(1.75^{+1.15}_{-1.05}) \cdot 10^{-10}$	$(0.854 {}^{+0.116}_{-0.098}) \cdot 10^{-10}$	0.8
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	-	$(0.277 {}^{+0.028}_{-0.035}) \cdot 10^{-10}$	-

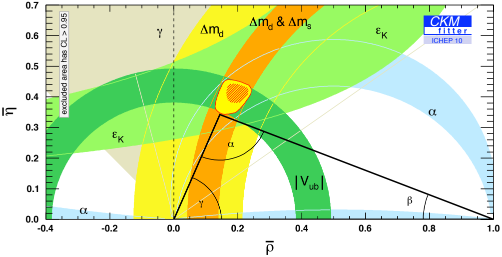
J. Charles et al., arXiv:1106.4041

…and spotting discrepancies to go beyond

Looking for discrepancies ?

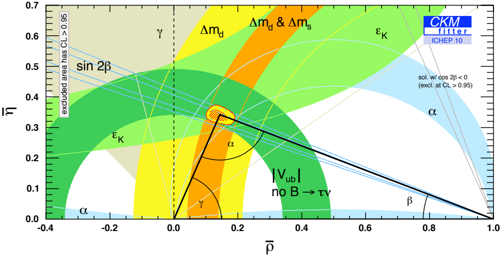
- $|V_{ub}|$ and $|V_{cb}|$ from semileptonic decays
  $\Longrightarrow$theoretical issue of uncertainties of lattice (excl.) vs OPE (incl.)
- ϵ_K vs $\sin(2\beta)$
  $\Longrightarrow$very dependent on the errors attached to B_K
- asymmetries in $B \to K\pi$
  $\Longrightarrow$difficulty of interpreting non-leptonic B decays
- $\sin(2\beta)$ vs $B \to \tau\nu$
- B_s mixing
- …

A discrepancy: sin(2β) vs $B \to \tau\nu$ (1)



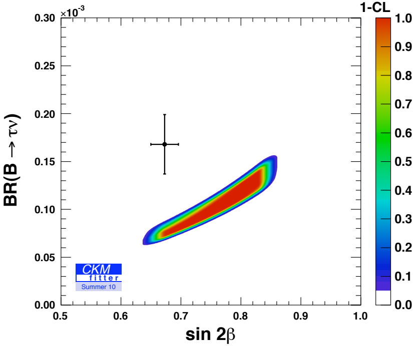
The global fit χ^2_{min} drops by $\sim 2.8\sigma$ if we remove

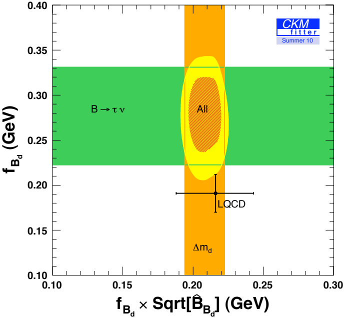
- $\sin 2\beta_{c\bar{c}}$



- or $B \to \tau\nu$

A discrepancy: $\sin(2\beta)$ vs $B \to \tau\nu$ (2)



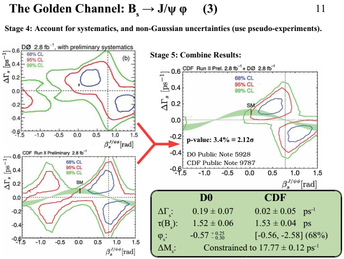


Issue *not only* the value of f_{B_d} since 2.9σ discrepancy from

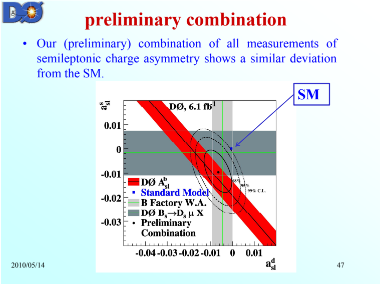
$$\frac{B(B\to\tau\nu)}{\Delta m_d} = \frac{3\pi}{4}\frac{m_\tau^2 \tau_B}{m_W^2 \eta_B S[x_t]}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 \frac{\sin^2\beta}{\sin^2(\alpha+\beta)}\frac{1}{|V_{ud}|^2 B_{B_d}}$$

Hadronic (lattice) inputs: $B(B\to\tau\nu)\propto f_{B_d}^2$, $B_d\bar{B}_d$ mixing $\Delta m_d \propto f_{B_d}^2 B_{B_d}$

Two more discrepancies out of the SM fit



$(\Delta\Gamma_s, \phi_s)$



Linear comb of a^d_{SL} and a^s_{SL}

- $B \to \tau\nu$ vs $\sin 2\beta$ — 1D constraint : 2.6 σ
- ϕ_s from $B_s \to J/\Psi\phi$ and τ_{FS} (null test) — 1D constraint : 2.1 σ
- A_{SL} (null test) — 1D constraint : 2.9 σ

$\Longrightarrow$Combination of χ^2 uncorrelated : 3.7 σ

[FPCP10/ICHEP10 ϕ_s not included, since no CDF/DØaverage]

Flavour sector in the Standard Model

$$\mathcal{L} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$$

Flavour sector in the Standard Model

$$\mathcal{L} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$$

Gauge part $\mathcal{L}_{gauge}(A_a, \Psi_j)$

- Highly symmetric (gauge and flavour symmetries)
- Well-tested experimentally
- Stable with respect to quantum corrections

Flavour sector in the Standard Model

$$\mathcal{L} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$$

Gauge part $\mathcal{L}_{gauge}(A_a, \Psi_j)$

- Highly symmetric (gauge and flavour symmetries)
- Well-tested experimentally
- Stable with respect to quantum corrections

Higgs part $\mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$

- Ad hoc description
- Dynamics untested (no Higgs seen yet)
- Not stable w.r.t quantum corrections
- Origin of flavour structure of the Standard Model
- First probe of Higgs interaction from…flavours physics
- CKM matrix = misalignement of Higgs-fermion Yukawa interactions between up- and down-sector

Modern view of the Standard Model

SM = effective low-energy theory

from an underlying, more fundamental and yet unknown, theory

As long as we stay at low energies, below the scale Λ of new particles

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

New operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Are made of SM fields and compatible with its symmetries

Two axes of experimental activity for NP

- Energy scale, underlying d.o.f. ? High-energy experiments
- Symmetries and structure ? High-precision (low-energy) expts

Constraints on NP from flavour physics

Mainly from loop-induced processes with quantum sensitivity to high scales and (ideally) are suppressed in the Standard Model

- Flavour Changing Neutral currents $\Delta F = 1$

$$B \to X_s\gamma, B \to X_s\ell^+\ell^-, B_s \to \ell^+\ell^-, K \to \pi\nu\bar{\nu}, K \to \pi\ell^+\ell^- \ldots$$

- Neutral-meson mixing $\Delta F = 2$

$$\Delta m_d, a_{CP}(J/\Psi K), \Delta m_s, a_{CP}(J/\Psi\phi), \Delta m_K, \epsilon_K \ldots$$

Constraints on NP from flavour physics

Mainly from loop-induced processes with quantum sensitivity to high scales and (ideally) are suppressed in the Standard Model

- Flavour Changing Neutral currents $\Delta F = 1$

$$B \to X_s\gamma, B \to X_s\ell^+\ell^-, B_s \to \ell^+\ell^-, K \to \pi\nu\bar{\nu}, K \to \pi\ell^+\ell^- \ldots$$

- Neutral-meson mixing $\Delta F = 2$

$$\Delta m_d, a_{CP}(J/\Psi K), \Delta m_s, a_{CP}(J/\Psi\phi), \Delta m_K, \epsilon_K \ldots$$

How to exploit the constraints ?

- Model-dependent approach: take your favourite model and see whether it survives all the tests (generally with fine-tuning)
- Model-independent approach: take a general framework, determine its parameters to guide model builders (who should explain suppression of operators)
- Require confidence in theoretical uncertainties for strong interaction (or poorly understood QCD will be turned into NP)

Constraints on NP from flavour physics

Mainly from loop-induced processes with quantum sensitivity to high scales and (ideally) are suppressed in the Standard Model

- Flavour Changing Neutral currents $\Delta F = 1$

$$B \to X_s\gamma, B \to X_s\ell^+\ell^-, B_s \to \ell^+\ell^-, K \to \pi\nu\bar{\nu}, K \to \pi\ell^+\ell^- \ldots$$

- Neutral-meson mixing $\Delta F = 2$

$$\Delta m_d, a_{CP}(J/\Psi K), \Delta m_s, a_{CP}(J/\Psi\phi), \Delta m_K, \epsilon_K \ldots$$

How to exploit the constraints ?

- Model-dependent approach: take your favourite model and see whether it survives all the tests (generally with fine-tuning)
- Model-independent approach: take a general framework, determine its parameters to guide model builders (who should explain suppression of operators)
- Require confidence in theoretical uncertainties for strong interaction (or poorly understood QCD will be turned into NP)

Power and limitation of model-independent approach in the following

Effective Hamiltonian

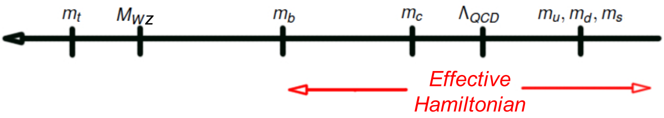
Making life slightly easier

Flavour physics mixes strong/weak interaction:

- Weak Lagrangian in terms of quarks, but hadronic final states
- Multi-scale problem $m_t, m_b, \Lambda_{QCD}, m_{light}$
- High-energies mixing SM and NP, whereas low energies SM only

Here scales of order m_b (or lower) !

so why not integrate out heavier degrees of freedom (t, W, Z) ?



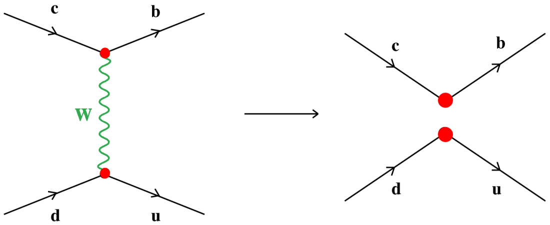
to get weak effective Hamiltonian $\mathcal{H}_{\rm eff}$

(still b, c, s, d, u, g and γ as dynamical particles)

Effective Hamiltonian

Fermi-like approach : μ separation between low and high energies

- Short distances : (perturbative) Wilson coefficients
- Long distances : local operator

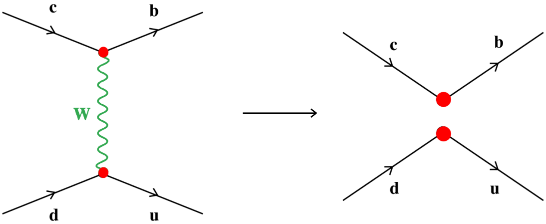


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

Effective Hamiltonian

Fermi-like approach : μ separation between low and high energies

- Short distances : (perturbative) Wilson coefficients
- Long distances : local operator

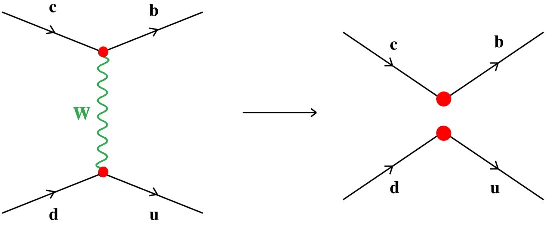


$$V_{ud} V_{cb}^{*} \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

Effective Hamiltonian

Fermi-like approach : μ separation between low and high energies

- Short distances : (perturbative) Wilson coefficients
- Long distances : local operator

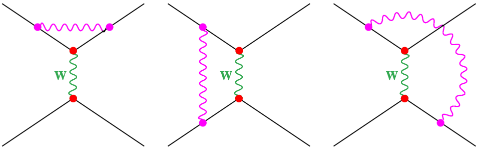


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5) d \bar{b}\gamma^\mu(1-\gamma_5) c$$

$$\mathcal{A}(B \to H) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i \, C_i(\mu) \, \langle H|\mathcal{O}_i|B\rangle(\mu)$$

- λ_i collect CKM-matrix elements,
- $C_i(\mu)$ Wilson coefficients (physics above m_b)
- matrix-elements of local operators $\mathcal{O}_i$

QCD effects



When we take into account one (or more) gluons

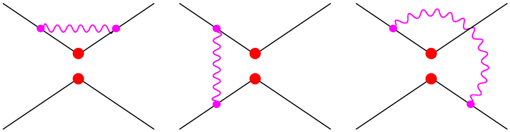
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} [C_1(\mu) Q_1(\mu) + C_2(\mu) Q_2(\mu)]$$

$$Q_1 = (\bar{b}_\alpha c_\beta)_{V-A} (\bar{u}_\beta d_\alpha)_{V-A}$$
$$Q_2 = (\bar{b}_\alpha c_\alpha)_{V-A} (\bar{u}_\beta d_\beta)_{V-A}$$

$$(\bar{b}c)_{V-A} = \bar{b}\gamma_\mu(1-\gamma_5)c$$

- new colour structures (flipped indices α, β)
- effective theory more divergent than SM, absorbed by renormalisation, inducing μ dependence
- C_1 and C_2 calculable fonctions of μ as perturbative series in α_s

Matching and Wilson coefficients



C_1 and C_2 so that full and effective theories yield same result

$$C_1(\mu) = -3\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2} + O(\alpha_s^2), \qquad C_2(\mu) = 1 + \frac{3}{N_c}\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2} + O(\alpha_s^2)$$

Separation of scales $-p^2 < \mu^2 < M_W^2$

$$\left(1 + \alpha_s X \log\frac{M_W^2}{-p^2}\right) = \left(1 + \alpha_s X \log\frac{M_W^2}{\mu^2}\right) \times \left(1 + \alpha_s X \log\frac{\mu^2}{-p^2}\right)$$

$$A_{full} = \int_{-p^2}^{M_W^2} \frac{dk^2}{k^2} = \int_{\mu^2}^{M_W^2} \frac{dk^2}{k^2} + \int_{-p^2}^{\mu^2} \frac{dk^2}{k^2} = C_i \otimes \langle O_i \rangle$$

Large logarithms

$$C_1(\mu) = -3\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2} + O(\alpha_s^2), \quad C_2(\mu) = 1 + \frac{3}{N_c}\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2} + O(\alpha_s^2)$$

- At low $\mu = m_b$, $\alpha_s(\mu) \times \log(M_W^2/\mu^2)$ not so small
  better to sum all terms like $\left(\alpha_s(\mu)\log\frac{M_W^2}{\mu^2}\right)^n$

Large logarithms

$$C_1(\mu) = -3\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2} + O(\alpha_s^2), \qquad C_2(\mu) = 1 + \frac{3}{N_c}\frac{\alpha_s}{4\pi}\log\frac{M_W^2}{\mu^2} + O(\alpha_s^2)$$

- At low $\mu = m_b$, $\alpha_s(\mu) \times \log(M_W^2/\mu^2)$ not so small

  better to sum all terms like $\left(\alpha_s(\mu)\log\frac{M_W^2}{\mu^2}\right)^n$

- μ-dep. of α_s from renormalisation group equation (RGE)

$$\frac{d\alpha_s(\mu)}{d\log\mu} = -2\beta_0\frac{\alpha_s^2}{4\pi} - 2\beta_1\frac{\alpha_s^3}{(4\pi)^2} + \ldots$$

  - $\beta_0 = (11N_c - 2N_f)/3$ from 1-loop vacuum polarisation
  - $\beta_1 = (34N_c^2 - 10N_cN_f - 3(N_c^2-1)N_f/N_c)/3$ from 2 loops
  - $\log\mu$ dependence reflects divergences occuring at each loop

(Next-to-...) Leading Logarithms in α_s

- Keeping only first order in $d\alpha_s/d\log\mu$ and solving

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 - \beta_0 \frac{\alpha_s(\mu_0)}{2\pi} \log(\mu_0/\mu)} = \alpha_s(\mu_0)\left[1 + \sum_{n=1}^{\infty}\left(\beta_0 \frac{\alpha_s(\mu_0)}{2\pi} \log\frac{\mu_0}{\mu}\right)^n\right]$$

- provides resummation of leading logs $\alpha_s^n(\mu_0)\log^n(\mu_0/\mu)$
  needed for $\mu \ll \mu_0$: $\alpha_s(\mu_0) \ll 1$ but $\alpha_s(\mu_0)\log(\mu_0/\mu) = O(1)$

(Next-to-...) Leading Logarithms in α_s

- Keeping only first order in $d\alpha_s/d\log\mu$ and solving

$$\alpha_s(\mu) = \frac{\alpha_s(\mu_0)}{1 - \beta_0 \frac{\alpha_s(\mu_0)}{2\pi}\log(\mu_0/\mu)} = \alpha_s(\mu_0)\left[1 + \sum_{n=1}^{\infty}\left(\beta_0 \frac{\alpha_s(\mu_0)}{2\pi}\log\frac{\mu_0}{\mu}\right)^n\right]$$

- provides resummation of leading logs $\alpha_s^n(\mu_0)\log^n(\mu_0/\mu)$
  needed for $\mu \ll \mu_0$: $\alpha_s(\mu_0) \ll 1$ but $\alpha_s(\mu_0)\log(\mu_0/\mu) = O(1)$

LO	1			
NLO	$\alpha_s(\mu_0)\log(\mu_0/\mu)$	$\alpha_s(\mu_0)$		
$NNLO$	$\alpha_s^2(\mu_0)\log^2(\mu_0/\mu)$	$\alpha_s^2(\mu_0)\log(\mu_0/\mu)$	$\alpha_s^2(\mu_0)$	
...	...	...	...	...
	Leading Logs	Next – to – Leading Logs	NNLL	...
	RGE LO	RGE NLO	RGE NNLO	...

$d\alpha_s/d\log\mu$ through $(k+1)$-loop computation
provides the resumation of (next-to-)^k leading log contributions

(Next-to-...) Leading Logarithms in Wilson Coeffs

- Introducing $Q_\pm = (Q_2 \pm Q_1)/2$, $C_\pm = C_2 \pm C_1$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} [C_+(\mu) Q_+(\mu) + C_-(\mu) Q_-(\mu)]$$

μ independence of the effective Hamiltonian yields RGE for C's

$$\frac{dC_\pm(\mu)}{d\log\mu} = \gamma_\pm(\mu) C_\pm(\mu) \qquad \gamma_\pm = \pm\frac{\alpha_s(\mu)}{4\pi}\frac{6(N_c \mp 1)}{N_c}$$

with mixing between C_1 and C_2

(Next-to-...) Leading Logarithms in Wilson Coeffs

- Introducing $Q_\pm = (Q_2 \pm Q_1)/2$, $C_\pm = C_2 \pm C_1$

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} [C_+(\mu) Q_+(\mu) + C_-(\mu) Q_-(\mu)]$$

μ independence of the effective Hamiltonian yields RGE for C's

$$\frac{d C_\pm(\mu)}{d \log \mu} = \gamma_\pm(\mu) C_\pm(\mu) \qquad \gamma_\pm = \pm \frac{\alpha_s(\mu)}{4\pi} \frac{6(N_c \mp 1)}{N_c}$$

with mixing between C_1 and C_2

- Dependence of α_s on μ

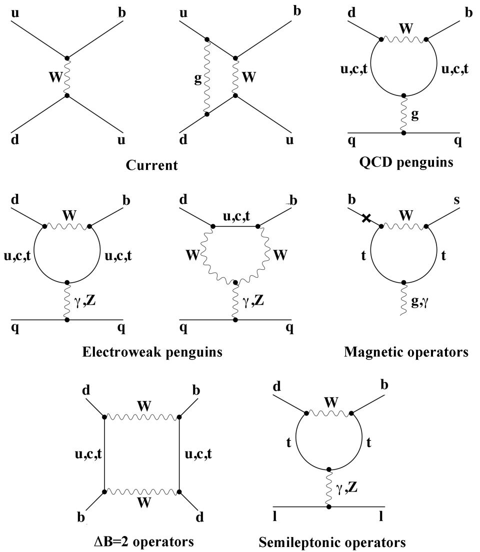
$$\frac{dg_s(\mu)}{\log \mu} = \beta(g_s(\mu)) = -\beta_0 \frac{g_s^3}{16\pi^2} + \ldots \qquad \beta_0 = \frac{11 N_c - 2 N_f}{3}$$

$$\longrightarrow C_\pm(\mu) = \left[\frac{\alpha_s(M_W)}{\alpha_s(\mu)}\right]^{\frac{\gamma_\pm^{(0)}}{\beta^{(0)}}} C_\pm(M_W) \qquad \gamma_\pm^{(0)} = \frac{6(N_c \mp 1)}{N_c}$$

$\Longrightarrow$Resumming leading logarithms in Wilson coefficients

SM operators of interest for heavy flavours

- Current-curent $O_{1,2}$
  - $(\bar{b}u)_{V-A}(\bar{u}d)_{V-A}$,
  - $(\bar{b}_i u_j)_{V-A}(\bar{u}_j d_i)_{V-A}$
- QCD penguins $O_{3,4,5,6}$
  - $(\bar{b}d)_{V-A}\sum_q(\bar{q}q)_{V\pm A}$,
  - $(\bar{b}_i d_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V\pm A}$
- E.weak penguins $O_{7,8,9,10}$
  - $(\bar{b}d)_{V-A}\sum_q e_q(\bar{q}q)_{V\pm A}$,
  - $(\bar{b}_i d_j)_{V-A}\sum_q e_q(\bar{q}_j q_i)_{V\pm A}$
- Magnetic operators $O^{\gamma}_{7,8}$
  - $\frac{e}{8\pi^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)bF_{\mu\nu}$,
  - $\frac{g}{8\pi^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)bG_{\mu\nu}$
- $\Delta B = 2$ operators $O_{|\Delta B|=2}$
  - $(\bar{b}d)_{V-A}(\bar{b}d)_{V-A}$
- $O^{\ell\ell}_{9,10}$ $(\bar{b}s)_{V-A}(\bar{e}e)_{V/A}$



Inclusive vs exclusive

$$A(B \to H) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle Q_i \rangle (\mu)$$

Inclusive decays

- $\sum_X |A(B \to X)|^2 \propto Im\langle B|\mathcal{T}|B\rangle \qquad \mathcal{T} = \int d^4x T[\mathcal{H}_{eff}(x)\mathcal{H}_{eff}(0)]$
- OPE + Quark hadron duality: $\mathcal{T} \propto O_0 + O_1/m_b + O_2/m_b^2 + \ldots$
- Perturbative part: O_0 up to same $O(\alpha_s^n)$ as Wilson coeffs
- Difficult to estimate/extract non-perturbative corrections $O_{n\geq 1}$
- Issues with kinematical cuts, quark hadron duality violation...

Exclusive decays

- $\langle H|Q_i|B\rangle(\mu)$ reexpressed in terms of decay constants, form factors (easy for one-body final state, much harder for 2-body)
- From lattice QCD, light-cone sum rules, with issues on systematics

Advantages of effective Hamiltonian

$$A(B \to H) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle Q_i \rangle(\mu)$$

- Simplification of the problem, keeping only relevant d.o.f. (light quarks, low-energy γ, leptons)
- Matching to fundamental theory at a high scale M_W ($O(\alpha_s^n)$) and renormalisation of operators $O(\alpha_s^{n+1})$
  $\Longrightarrow$resummation of (next-to-)^n leading logs in $C(\mu)$
- Connection between different processes sharing the same high-energy dynamics (penguins, boxes…)

Advantages of effective Hamiltonian

$$A(B \to H) = \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \langle Q_i \rangle (\mu)$$

- Simplification of the problem, keeping only relevant d.o.f. (light quarks, low-energy γ, leptons)
- Matching to fundamental theory at a high scale M_W ($O(\alpha_s^n)$) and renormalisation of operators $O(\alpha_s^{n+1})$
  $\Longrightarrow$resummation of (next-to-)^n leading logs in $C(\mu)$
- Connection between different processes sharing the same high-energy dynamics (penguins, boxes...)

Implementation of NP in an "almost" model-independent way

- change values of C (straitghtforward theoretically)
  $\Longrightarrow$Illustration with NP in neutral-meson mixing
- include new Q (check observable sensitivity and operator mixing)
  $\Longrightarrow$Illustration with NP in $b \to s\gamma^{(*)}$

New Physics in meson mixing

Neutral-B mixing

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

M and Γ hermitian: mixing due to off-diagonal terms $M_{12}^q - i\Gamma_{12}^q/2$

$\Longrightarrow$Diagonalisation: physical $|B_{H,L}^q\rangle$ of masses $M_{H,L}^q$, widths $\Gamma_{H,L}^q$

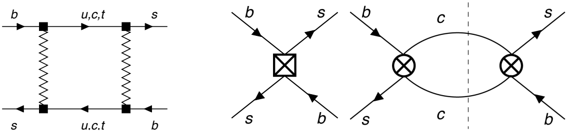
In terms of M_{12}^q, $|\Gamma_{12}^q|$ and $\phi_q = arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$ [small in SM]

- Mass difference $\Delta M_q = M_H^q - M_L^q = 2|M_{12}^q|$
- Width difference $\Delta\Gamma_q = \Gamma_H^q - \Gamma_L^q = 2|\Gamma_{12}^q|\cos(\phi_q)$
- Asymmetry $a_{SL} = \frac{\Gamma(\bar{B}^q(t)\to\ell^+\nu X)-\Gamma(B^q(t)\to\ell^-\nu X)}{\Gamma(\bar{B}^q(t)\to\ell^+\nu X)+\Gamma(B^q(t)\to\ell^-\nu X)} = \frac{|\Gamma_{12}^q|}{|M_{12}^q|}\sin\phi_q$

p/q from mixing in time-dependent analysis of B decays

"phase" $\phi_{M_q} \simeq arg(M_{12}^{q*}) + O\left(\frac{|\Gamma_{12}^q|}{|M_{12}^q|}\right)$

Mixing observables in SM



[Beneke et al 1996-98, Nierste and Lenz 2006]

Effective Hamiltonian approach for inclusive quantities

- M_{12}^q dominated by dispersive part of top boxes
  - involve one operator at LO: $Q = \bar{q}_L \gamma_\mu b_L \bar{q}_L \gamma^\mu b_L$
- Γ_{12}^q dominated by absorptive part of charm boxes
  - non local contribution, expressed as expansion in $1/m_b$
  - involve two operators at LO: Q and $\tilde{Q}_S = \bar{q}_L^\alpha b_R^\beta \bar{q}_L^\beta b_R^\alpha$
- $\Delta\Gamma_s, \Delta\Gamma_s/\Delta M_s, a_{SL}^s$ as functions of bag parameters B, B_S and decay constant parametrising value of operators Q, $\tilde{Q}_S$

New Physics in $\Delta F = 2$

- $B \to \tau\nu$ vs $(\sin 2\beta, \Delta m_d)$
- ϕ_s from $B_s \to J/\Psi\phi$ and τ_{FS}
- A_{SL} from like-sign dimuon charge asymmetry

Framework: New Physics only in $\Delta F = 2$ processes

- M_{12} dominated by short distances (top boxes) [affected by NP]
- Γ_{12} dominated by tree decays into charm [not affected by NP]
- Tree level (4 diff flavours) processes not affected by New Physics
- Model-independent parametrisation

$$\langle B_q|\mathcal{H}_{eff}^{SM+NP}|\bar{B}_q\rangle = \langle B_q|\mathcal{H}_{eff}^{SM}|\bar{B}_q\rangle \times [Re(\Delta_q) + i \cdot Im(\Delta_q)]$$

$\Longrightarrow$New physics only changing modulus and phase of M_{12}^q

[A. Lenz et al., PRD83 (2011) 036004]

Three different "model-independent" hypotheses

- Framework: NP only in $\Delta F = 2$ operators
- Scenarios (from the more specific to the more general)
  - A : Minimal Flavour Violation with small bottom Yukawa coupling

$$H^{|\Delta B|=2} = (V_{tq}^* V_{tb})^2 CQ + h.c. \qquad C \text{ real}$$

$\Delta_d = \Delta_s$ real, related to K-meson

  - B : MFV with large bottom Yukawa coupling

$$H^{|\Delta B|=2} = (V_{tq}^* V_{tb})^2 [CQ + C_S Q_S + \tilde{C}_S \tilde{Q}_S] + h.c.$$

$\Delta_d = \Delta_s$ complex, unrelated to K-meson

  - C : Non Minimal Flavour Violation

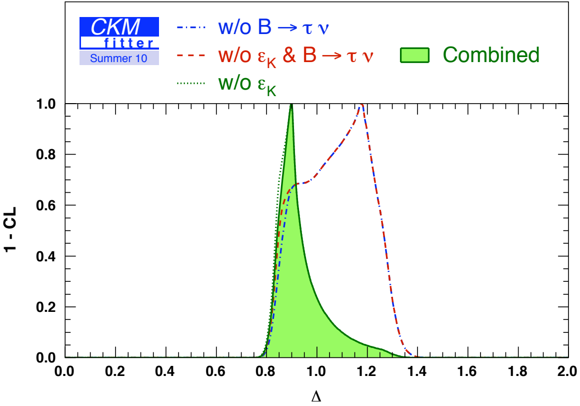
$$H^{|\Delta B|=2} = (V_{tq}^* V_{tb})^2 C_q Q + h.c.$$

Δ_d and Δ_s complex independent, unrelated to K-meson

- Observables: Separated into CKM-fixing part and NP-fixing part

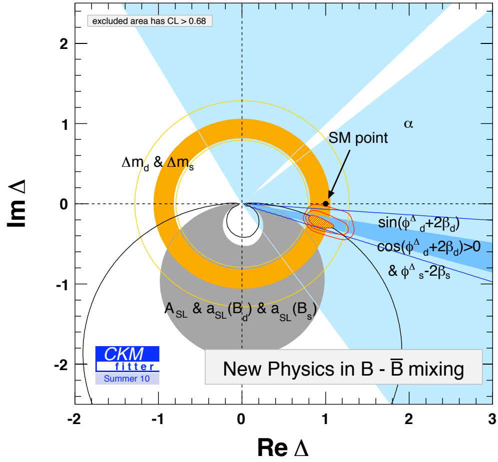
Scenario A: $\Delta_d = \Delta_s = \Delta$ real

- Most limited extension: $\Delta_d = \Delta_s$ real, related to $K\bar{K}$ mixing
- Compatible with 1, not much better than SM for discrepancies



2D SM hypothesis ($\Delta = 1 + i \cdot 0$): 3.7 σ

Scenario B: $\Delta_d = \Delta_s = \Delta$ complex

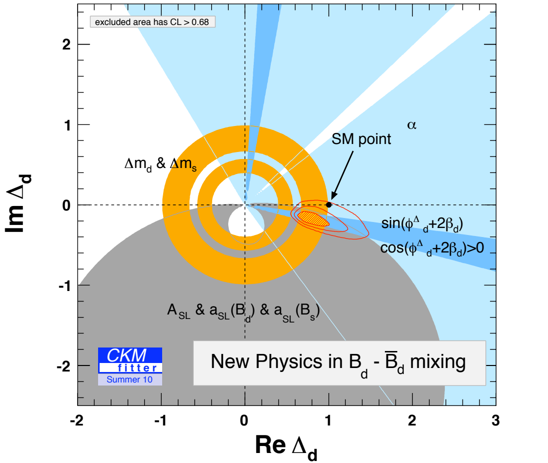


[Constraints 68% CL]

- Discrepancy from $Br(B \to \tau\nu)$ shifts β constraint from real axis
- Disagreement with SM driven in same dir by $Br(B \to \tau\nu)$, ϕ_s and A_{SL}

2D SM hypothesis ($\Delta = 1 + i \cdot 0$): 3.3 σ

Scenario C: $\Delta_d \neq \Delta_s$ - B_d mixing

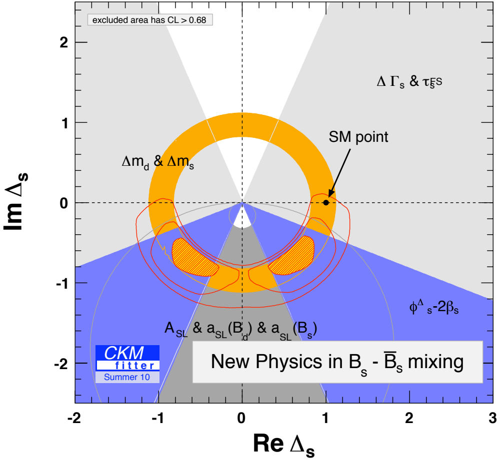


[Constraints 68% CL]

- Dominant const from β and Δm_d (2 sols. for apex of unitarity triangle)
- Tension from $Br(B \to \tau\nu)$ shifts β constraint from real axis
- Disagreement with SM driven in same dir by $Br(B \to \tau\nu)$ and A_{SL}

2D SM hypothesis ($\Delta_d = 1 + i \cdot 0$): 2.7 σ

Scenario C: $\Delta_d \neq \Delta_s$ - B_s mixing



[Constraints 68% CL]

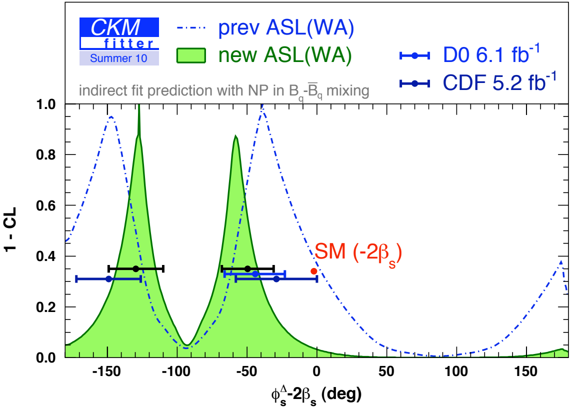
- Dominant constraints from Δm_s, ϕ_s and A_{SL}
- Disagreement with SM driven in same dir by ϕ_s and A_{SL}

2D SM hypothesis ($\Delta_s = 1 + i \cdot 0$): 2.7σ

Scenario C: Prediction for ϕ_s

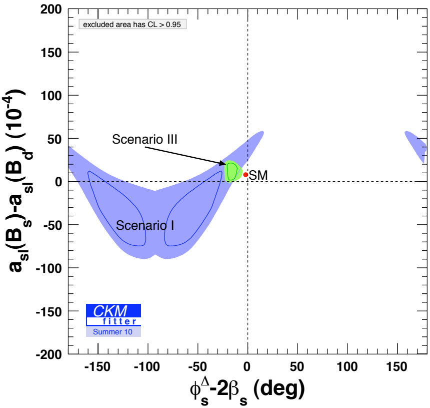
Possible to predict "ϕ_s" from $B_s \to J/\Psi\phi$ and to compare with current measurements

[average or recent CDF/D0 separately]



All scenarios: Predictions for $a_{SL}^d - a_{SL}^s$

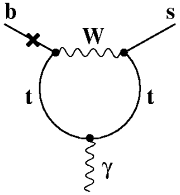
Possible to predict $a_{SL}^d - a_{SL}^s = f(\phi_s|_{B_s \to J/\Psi\phi})$ and to compare with present/future measurements



- SM = A ($\Delta_d = \Delta_s$ real)
- Scenario III = B ($\Delta_d = \Delta_s$ complex)
- Scenario I = C ($\Delta_d \neq \Delta_s$ both complex)

New Physics in radiative decays

Radiative decays as probes of New Physics



$b \to D\gamma^{(*)}$ with $D = d, s$

- access to $|V_{t(d,s)}|$ within SM
- cross-check of neutral B mixing (box/penguin)
- loop processes very sensitive to NP

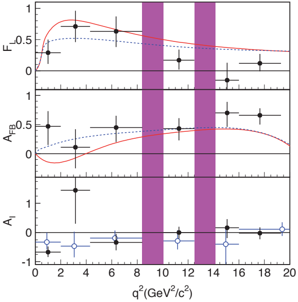
In terms of effective Hamiltonian main contributions from:

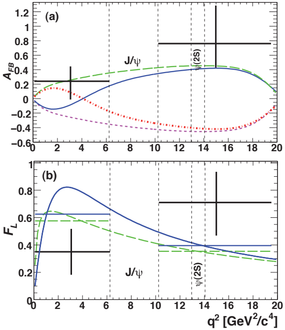
- Electromagnetic dipole: $O_7 = \frac{e}{16\pi^2} m_b \bar{D}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$
- Semileptonic (vector) operator: $O_9 = \frac{e^2}{16\pi^2} \bar{D}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\ell$
- Semileptonic (axial) operator: $O_{10} = \frac{e^2}{16\pi^2} \bar{D}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma_\mu\gamma_5\ell$
- $b \to s\gamma$: O_7 only, $b \to s\ell^+\ell^-$: $O_{7,9,10}$
- chirality of operators related to W exchange
- New physics changes Wilson coeffs and/or adds new operators

The example of the flipped-sign solution

$C_7 \to -C_7^{SM}$?

- No change for $B(B \to X_s\gamma)$ (not sensitive to phase of C_7)





- Indication in Belle/Babar data on $B \to K^*\ell^+\ell^-$
- Accomodate no zero in FB asymmetry

- In “contradiction” with $B \to X_s\ell^+\ell^-$ [Gambino, Haisch, Misiak]
- Statements dependent on structure of NP allowed in $b \to s\gamma(^*)$ (all these observables involve also chirally-flipped operators)

Framework

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\left(V_{tb}V_{ts}^*\mathcal{H}_{\rm eff}^{(t)} + V_{ub}V_{us}^*\mathcal{H}_{\rm eff}^{(u)}\right) + h.c.,$$

with dipole and semileptonic operators, SM and chirally-flipped

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad \mathcal{O}_{7'} = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{9'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell), \qquad \mathcal{O}_{10'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5 \ell),$$

$P_{L,R} = (1 \mp \gamma_5)/2$ projection over the chiralities

- In SM, matching at $\mu_0 = 2M_W$, and down to $\mu_b = 4.8$ GeV

$$C_7^{\rm eff}(\mu_b) = -0.29 \qquad C_9(\mu_b) = 4.07, \qquad C_{10}(\mu_b) = -4.31$$

- Separate mixing among SM ops. and among chirally-flipped ops.

Framework, scenarios and observables

- Framework: NP in dipole and semileptonic operators (SM and chirally-flipped) through real shift in Wilson coefficients
- Scenarios (from the more specific to the more general)
  - A : NP in 7,7' only
  - B : NP in 7,7', 9,10 only
  - C : NP in 7,7',9,10,9',10' only
- Observables
  - CKM part fixed from global fit (no input from radiative decay)
  - Class-I: observables sensitive only to $7, 7'$
  - Class-II: observables sensitive only to $7, 7', 9, 9', 10, 10'$
  - Class-III: observables sensitive to $7, 7', 9, 9', 10, 10'$ and other operators (scalar...)

[SDG et al., hep-ph/1104.3342]

Observables

With limited sensitivity to hadronic inputs/strongly constraining

- Class-I: sensitive only to $7, 7'$ ($b \to s\gamma$ only)
  - Branching ratio $\mathcal{B}(B \to X_s\gamma)$
  - $B \to K^*\gamma$: exclusive time-dependent CP asymmetry $S_{K^*\gamma}$
  - $B \to K^*\gamma$: isospin asymmetry $A_I(B \to K^*\gamma)$

Observables

With limited sensitivity to hadronic inputs/strongly constraining

- Class-I: sensitive only to $7, 7'$ ($b \to s\gamma$ only)
  - Branching ratio $\mathcal{B}(B \to X_s\gamma)$
  - $B \to K^*\gamma$: exclusive time-dependent CP asymmetry $S_{K^*\gamma}$
  - $B \to K^*\gamma$: isospin asymmetry $A_I(B \to K^*\gamma)$
- Class-II: sensitive only to $7, 7', 9, 9', 10, 10'$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 transverse asymmetry $\tilde{A}_T^2$ (not measured yet)

Observables

With limited sensitivity to hadronic inputs/strongly constraining

- Class-I: sensitive only to $7, 7'$ ($b \to s\gamma$ only)
  - Branching ratio $\mathcal{B}(B \to X_s\gamma)$
  - $B \to K^*\gamma$: exclusive time-dependent CP asymmetry $S_{K^*\gamma}$
  - $B \to K^*\gamma$: isospin asymmetry $A_I(B \to K^*\gamma)$
- Class-II: sensitive only to $7, 7', 9, 9', 10, 10'$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 transverse asymmetry $\tilde{A}_T^2$ (not measured yet)
- Class-III: sensitive to all these and other ops. (scalar. . .)
  - Branching ratio $\mathcal{B}(B \to X_s l^+ l^-)$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 polarisation fraction $\tilde{F}_L$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 forward-backward asymmetry $\tilde{A}_{FB}$

Observables

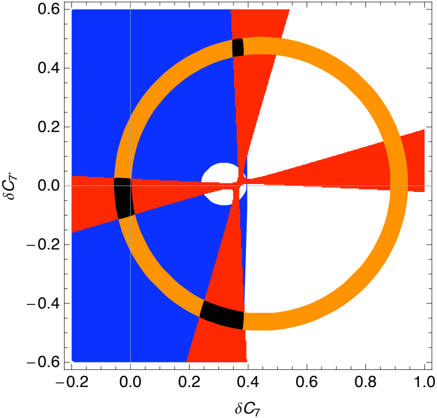
With limited sensitivity to hadronic inputs/strongly constraining

- Class-I: sensitive only to $7, 7'$ ($b \to s\gamma$ only)
  - Branching ratio $\mathcal{B}(B \to X_s\gamma)$
  - $B \to K^*\gamma$: exclusive time-dependent CP asymmetry $S_{K^*\gamma}$
  - $B \to K^*\gamma$: isospin asymmetry $A_I(B \to K^*\gamma)$
- Class-II: sensitive only to $7, 7', 9, 9', 10, 10'$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 transverse asymmetry $\tilde{A}_T^2$ (not measured yet)
- Class-III: sensitive to all these and other ops. (scalar…)
  - Branching ratio $\mathcal{B}(B \to X_s l^+ l^-)$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 polarisation fraction $\tilde{F}_L$
  - $B \to K^*\ell^+\ell^-$: integrated low-q^2 forward-backward asymmetry $\tilde{A}_{FB}$

- Express all quantities in terms of $\delta C_i = C_i(\mu_b) - C_i^{SM}(\mu_b)$
- Plot "naive" constraints $|X_{th}(\delta C_i) - X_{exp}| \leq \Delta X_{th} + \Delta X_{exp}$
- Uncertainties ΔX_{th} from SM analysis

(assumed not to be modified significantly by NP)

$\delta C_7, \delta C_{7'}$ plane : constraints at 1 σ



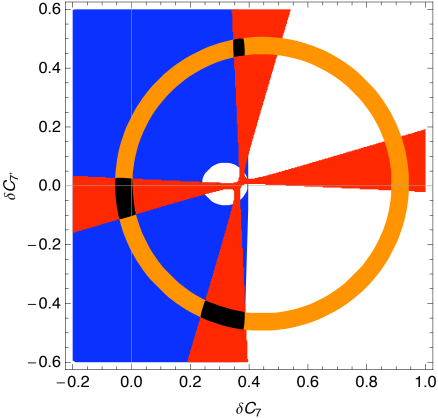
Class I observables

- A_I (blue)
- $B(B \to X_s\gamma)$ (orange)
- $S_{K^*\gamma}$ (red)

Combined regions (black)

- SM solution $(C_7, C_{7'}) = (C_7^{SM}, 0)$
- two non-SM solutions $(C_7, C_{7'}) = (0, \pm 0.4)$

$\delta C_7, \delta C_{7'}$ plane : constraints at 1 σ



Class I observables

- A_I (blue)
- $B(B \to X_s\gamma)$ (orange)
- $S_{K^*\gamma}$ (red)

Combined regions (black)

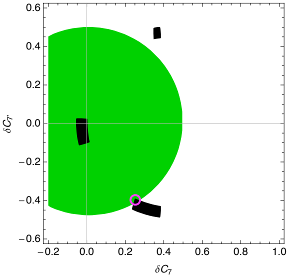
- SM solution $(C_7, C_{7'}) = (C_7^{SM}, 0)$
- two non-SM solutions $(C_7, C_{7'}) = (0, \pm 0.4)$

- In qualitative agreement with [Bobeth et al, Hurth et al]
- A_I disfavours flipped-sign solution $(C_7, C_{7'}) \simeq (-C_7^{SM}, 0)$
  $\Longrightarrow$Same conclusion as [Gambino, Haisch, Misiak]
  without using $B \to X_s\mu^+\mu^-$ (less dependent on NP scenario)

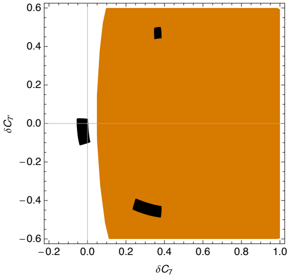
Scenario A : class-III observables

In Scenario A, no NP apart from $C_7, C_{7'}$

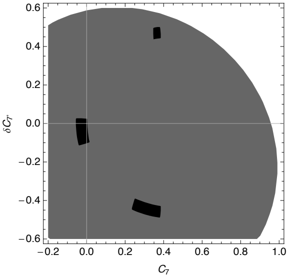
$\Longrightarrow$class-III observables constrain also the shifts $\delta C_7, \delta C_{7'}$



$\mathrm{B}(B \to X_s \mu^+ \mu^-)$
$(\delta C_7, \delta C_{7'})$



$\tilde{A}_{FB}$
$(\delta C_7, \delta C_{7'})$

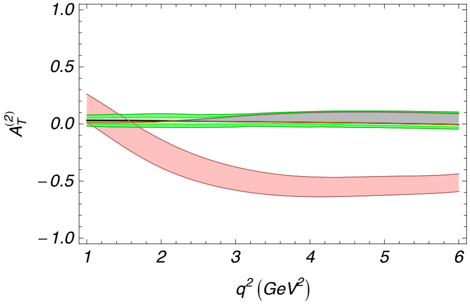


$\tilde{F}_L$
$(\delta C_7, \delta C_{7'})$

- $\mathrm{B}(B \to X_s \mu^+ \mu^-)$ more for SM-like region [Gambino, Haisch, Misiak]
- $\tilde{A}_{FB}$ slightly in favour of non-SM regions

$\Longrightarrow$Allowed: SM region and region around $(C_7, C_{7'}) = (0, -0.4)$

Scenario A : prediction for A_T^2

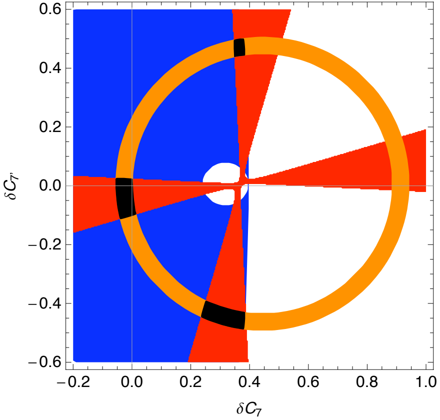


- In the SM (green, including uncertainties from form factors and estimate of $1/m_b$-suppressed corrections)
- Under scenario A, non-SM region provides very different values of A_T^2 (pink)

Scenario B : class-I constraints in $(\delta C_7, \delta C_{7'})$

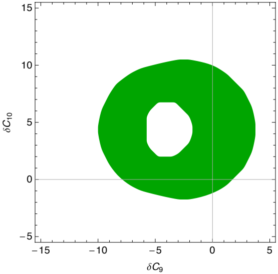
In Scenario B, NP in

- $C_7, C_{7'}$: same constraints as before from class-I observables

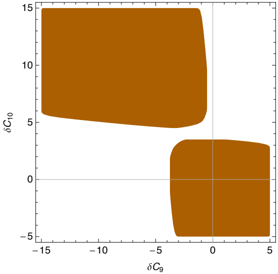


In Scenario B, NP in

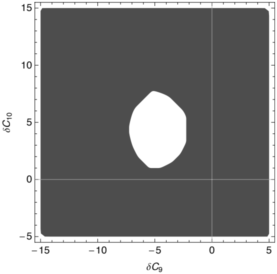
- $C_7, C_{7'}$: same constraints as before from class-I observables
- C_9, C_{10}: to be fixed from class-III observables



$\mathcal{B}(B \to X_s \mu^+ \mu^-)$
$(\delta C_9, \delta C_{10})$



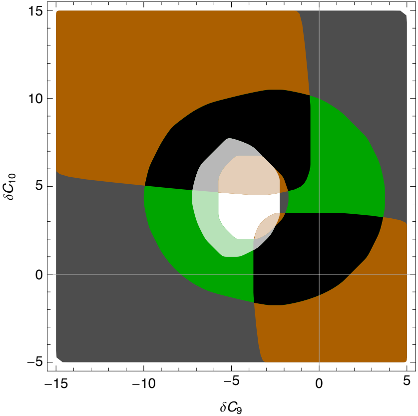
$\tilde{A}_{FB}$
$(\delta C_9, \delta C_{10})$



$\tilde{F}_L$
$(\delta C_9, \delta C_{10})$

- Small absolute values of (C_9, C_{10}) disfavoured
- Qualitative agreement with [Hurth et al.]

Scenario B : Overlap and non-SM regions

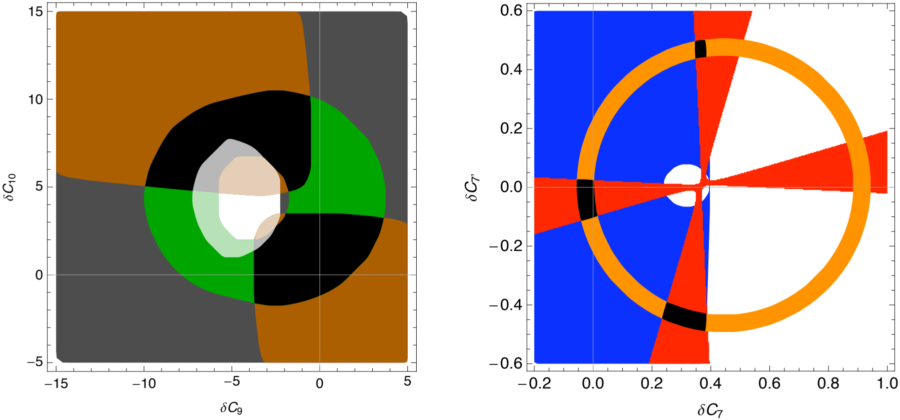


- $B(B \to X_s \mu^+ \mu^-)$ (green)
- $A_{\rm FB}$ (brown)
- $F_{\rm L}$ (grey)

Two combined regions (black)

- SM region around $(C_9, C_{10}) = (C_9^{SM}, C_{10}^{SM})$
- non-SM region around $(C_9, C_{10}) = (-C_9^{SM}, -C_{10}^{SM})$

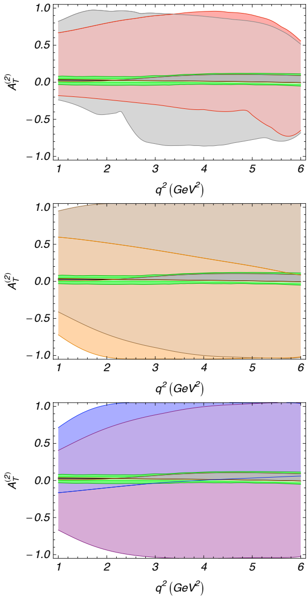
Scenario B : Overlap and non-SM regions



Both combined regions in (C_9, C_{10}) can accomodate values of $(C_7, C_{7'})$ either in the SM region or the two non-SM ones.

$\Longrightarrow$Scenario B NP may alter $(C_7, C_{7'})$ and/or (C_9, C_{10}) and reproduce the experimental value $B \to X_s\mu^+\mu^-$ at the same time

Scenario B : prediction for class-II obs. $A_T^2(q^2)$



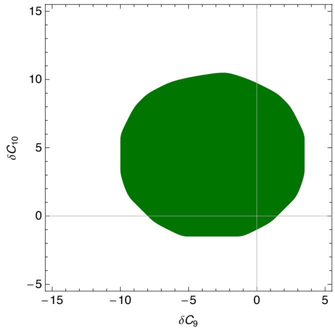
- $A_T^2(q^2)$ for $q^2 = 1 \ldots 6$ GeV^2
- Different shapes for the three regions in $(C_7, C_{7'})$
  - $(\delta C_7, \delta C_{7'}) \simeq (0, 0)$
  - $(\delta C_7, \delta C_{7'}) \simeq (0.3, -0.4)$
  - $(\delta C_7, \delta C_{7'}) \simeq (0.3, 0.4)$
  - two possibilities for SM and non-SM regions for (C_9, C_{10})
- Very large uncertainties due to the size of the two regions for (C_9, C_{10}) (in particular from non-SM region)
- To be improved with use of q^2-dependent obs.

Scenario C : class-III observables

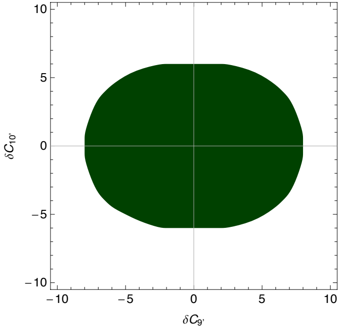
In Scenario C, NP in

- $C_7, C_{7'}$: same constraints as before from class-I observables
- $C_9, C_{10}, C_{9'}, C_{10'}$: to be fixed from class-III observables

Actually, only B($B \to X_s \mu^+ \mu^-$) still yields constraints



$(\delta C_9, \delta C_{10})$



$(\delta C_9', \delta C_{10}')$

$\Longrightarrow$Too many possibilities to get a prediction for A_T^2

A few observables for $\Delta F = 1$

$1('), 2(')$: tree decays $\quad$ $3('), 4('), 5('), 6(')$: penguin decays

	Hadronic	$7('), 8(')$	9(')	10(')	S, P	$\nu\bar{\nu}$	Mixing
$B \to K^*\gamma$	×	×					
$S_{K^*\gamma}$		×					×
A_I	×	×					
$B \to X_s\gamma$		×					
A_{CP}		× (Im)					
$B \to K(^*)\ell^+\ell^-$	×	×	×	×	×		
A_I	×	×	×	×	×		
A_{FB}, F_L		×	×	×	×		
A_T^2, A_T^5		×	×	×			
$B \to X_s\ell^+\ell^-$		×	×	×			
A_{FB}		×	×	×			
$B_s \to \mu\mu$	×			×	×		
$B \to K(^*)\nu\bar{\nu}$	×					×	
F_L						×	
$K \to \pi\nu\bar{\nu}$						×	

Outlook

Flavour dynamics undergoing transition from SM test to NP searches

- Flavour dynamics well tested, and in good overall agreement with SM expectations …but a few itches ($B \to \tau\nu$, $B_{d,s}$ mixing)
- Start exploring flavour constraints on NP in a bottom-up approach
- With the help of $\mathcal{H}_{eff}$, separating high and low energies elegantly
- And resumming large QCD corrections along the way

Outlook

Flavour dynamics undergoing transition from SM test to NP searches

- Flavour dynamics well tested, and in good overall agreement with SM expectations ...but a few itches ($B \to \tau\nu$, $B_{d,s}$ mixing)
- Start exploring flavour constraints on NP in a bottom-up approach
- With the help of $\mathcal{H}_{eff}$, separating high and low energies elegantly
- And resumming large QCD corrections along the way

Illustration with $\Delta F = 2$ transitions and $b \to s\gamma(^*)$

- "Model-independent" approach still restricted to some framework
- Importance of defining scenarios and identifying observables with sensitivities to different operators
- As well as exploiting q^2-dependence of observables
- Impact on predictions, as illustrated by $a_{SL}^d - a_{SL}^s$, A_T^2...

Outlook

Flavour dynamics undergoing transition from SM test to NP searches

- Flavour dynamics well tested, and in good overall agreement with SM expectations . . . but a few itches ($B \to \tau\nu$, $B_{d,s}$ mixing)
- Start exploring flavour constraints on NP in a bottom-up approach
- With the help of $\mathcal{H}_{eff}$, separating high and low energies elegantly
- And resumming large QCD corrections along the way

Illustration with $\Delta F = 2$ transitions and $b \to s\gamma(^*)$

- "Model-independent" approach still restricted to some framework
- Importance of defining scenarios and identifying observables with sensitivities to different operators
- As well as exploiting q^2-dependence of observables
- Impact on predictions, as illustrated by $a_{SL}^d - a_{SL}^s$, A_T^2. . .

More to come from next generation of flavour facitilies !

Back-up

Flavour and new physics

- Standard Model Flavour Puzzle
  Why is there a hierarchy of small parameters?
- New Physics Flavour Puzzle
  If new physics around 1 TeV, why so little seen in current flavour physics ? Why Flavour-Changing Neutral Currents are so small ?
- What about baryon asymmetry?
  Not enough CP for baryogenesis ; flavour matters in leptogenesis

Flavour and new physics

- Standard Model Flavour Puzzle
  Why is there a hierarchy of small parameters?
- New Physics Flavour Puzzle
  If new physics around 1 TeV, why so little seen in current flavour physics ? Why Flavour-Changing Neutral Currents are so small ?
- What about baryon asymmetry?
  Not enough CP for baryogenesis ; flavour matters in leptogenesis

Many different extensions of the SM

- Fermion content (more matter)
- Gauge boson content (more interactions)
- Different mechanism for ew symmetry breaking (more or no Higgs)
- Additional symmetries
- Additional dimensions

Supersymmetry, grand-unified, left-right symmetric, extra-dim, sequential models, 4th gen, Higgs multiplet, composite Higgs, little Higgs, Higgsless. . .

$|V_{ub}|$ inclusive and exclusive

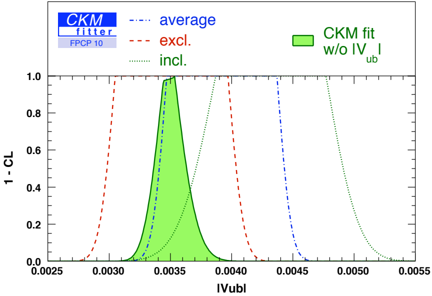
Two ways of getting $|V_{ub}|$:

- Inclusive : $b \to u\ell\nu$ + Operator Product Expansion
- Exclusive : $B \to \pi\ell\nu$ + Form factors

$$|V_{ub}|_{inc} = 4.32^{+0.21}_{-0.24} \pm 0.45$$
$$|V_{ub}|_{exc} = 3.51 \pm 0.10 \pm 0.46$$

$$|V_{ub}|_{ave} = 3.92 \pm 0.09 \pm 0.45$$

with all values $\times 10^{-3}$



- Discrepancy depends on statistical treatment
- Same problem for $|V_{cb}|$

From Higgs to Cabibbo-Kobayashi-Maskawa

- In $\mathcal{L}_{Higgs}$, general Yukawa interaction between Higgs and quarks

$$\bar{Q}_L^i Y_D^{ik} d_R^k \phi + \bar{Q}_L^i Y_U^{ik} u_R^k \phi + h.c. + \dots \qquad Q_L = (u_L, d_L)$$

- Vacuum expectation value for Higgs $\langle \phi \rangle \neq 0$ yields mass matrices

$$\bar{d}_L^i M_D^{ik} d_R^k + \bar{u}_L^i M_U^{ik} u_R^k + \dots$$

- Diagonalise the mass matrices to get mass eigenstates

$$m_q = \frac{y_q \langle \phi \rangle}{\sqrt{2}} \quad M_D = \mathrm{diag}(m_d, m_s, m_b) \qquad M_U = \mathrm{diag}(m_u, m_c, m_t)$$

- In mass eigenstates, charged currents involve rotation (CKM)

$$J_W^\mu = \bar{u}_L \gamma^\mu d_L \to \bar{u}_L V \gamma^\mu d_L$$

From Higgs to Cabibbo-Kobayashi-Maskawa

- In $\mathcal{L}_{Higgs}$, general Yukawa interaction between Higgs and quarks

$$\bar{Q}_L^i Y_D^{ik} d_R^k \phi + \bar{Q}_L^i Y_U^{ik} u_R^k \phi + h.c. + \dots \qquad Q_L = (u_L, d_L)$$

- Vacuum expectation value for Higgs $\langle \phi \rangle \neq 0$ yields mass matrices

$$\bar{d}_L^i M_D^{ik} d_R^k + \bar{u}_L^i M_U^{ik} u_R^k + \dots$$

- Diagonalise the mass matrices to get mass eigenstates

$$m_q = \frac{y_q \langle \phi \rangle}{\sqrt{2}} \quad M_D = \mathrm{diag}(m_d, m_s, m_b) \qquad M_U = \mathrm{diag}(m_u, m_c, m_t)$$

- In mass eigenstates, charged currents involve rotation (CKM)

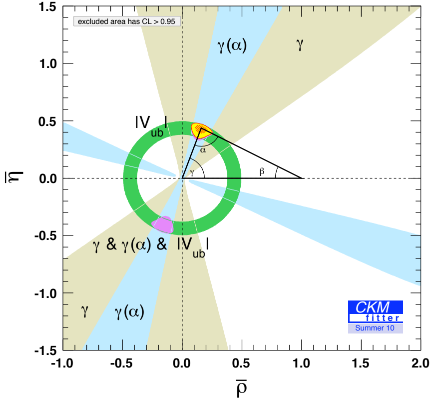
$$J_W^\mu = \bar{u}_L \gamma^\mu d_L \to \bar{u}_L V \gamma^\mu d_L$$

Flavour physics deeply connected with
the Yukawa interactions of Higgs and fermions

Separating observables for $\Delta F = 2$

Observables not affected by NP, used to fix CKM :

$|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, γ and $\gamma(\alpha) \equiv \pi - \alpha - \beta$ (ϕ_{B_d} cancels)



Observables affected by NP, used to determine Δ_d, Δ_s

- Neutral-meson oscillation Δm_d, Δm_s
- Lifetime difference $\Delta\Gamma_d$
- Time-dep asymmetries related to ϕ_{B_d}, ϕ_{B_s}
- Semileptonic asymmetries a^d_{SL}, a^s_{SL}, A_{SL}
- α (interference between decay and mixing)

Some of the inputs for $\Delta F = 2$

$$\Delta\Gamma_s = f[f_{Bs}, B, \tilde{B}_S; \mu, m_b^{pow}, B_{1/m_b} \ldots]$$
$$\Delta\Gamma_s/\Delta M_s = f[\tilde{B}_S/B; B_{1/m_b}, m_b^{pow}, \mu, \bar{m}_c \ldots]$$
$$a_{SL}^s = f[\tilde{B}_S/B; |V_{ub}/V_{cb}|, \gamma, \mu, \bar{m}_c, B_{1/m_b} \ldots]$$

- B_d, B_s, f_{B_d}, f_{B_d} parameters : average of unquenched 2 and 2+1 lattice estimates
- Bag parameters for scalar operators from quenched lattice estimate [Becirevic et al., 2002]

$$\tilde{B}'^s_S(m_b)/\tilde{B}'^d_S(m_b) = 1.00 \pm 0.03 \quad \tilde{B}'^s_S(m_b) = 1.40 \pm 0.13$$

- $1/m_b$ suppressed operators: bag parameters (vacuum insertion approximation) and power correction scale

$$B_{Ri}(m_b) = 1.0 \pm 0.5 \qquad m_b^{\text{pow}} = 4.70 \pm 0.10$$

- charm quark mass from $\sigma(e^+e^- \to c\bar{c})$ sum rules to 3- and 4-loops [Steinhauser and Kühn 2001-04, Jamin and Hoang 2004]

Some of the inputs for radiative decays

$\mu_b = 4.8$ GeV $[/2 \to \times 2]$	$\mu_0 = 2M_W$ $[/2 \to \times 2]$
$\sin^2\theta_W = 0.2313$ $\alpha_{em}(M_Z) = 1/128.940$	 $\alpha_s(M_Z) = 0.1184 \pm 0.0007$
$m_t^{\rm pole} = 173.3 \pm 1.1$ GeV $m_c^{\overline{MS}}(m_c) = 1.27 \pm 0.09$ GeV	$m_b^{1S} = 4.68 \pm 0.03$ GeV $m_s^{\overline{MS}}(2\text{ GeV}) = 0.101 \pm 0.029$ GeV
$\lambda_{CKM} = 0.22543 \pm 0.0008$ $\bar\rho = 0.144 \pm 0.025$	$A_{CKM} = 0.805 \pm 0.020$ $\bar\eta = 0.342 \pm 0.016$
$\mathcal{B}(B \to X_c e\bar\nu) = 0.1061 \pm 0.00017$ $\lambda_2 = 0.12$ GeV^2	$C = 0.58 \pm 0.016$
$\Lambda_h = 0.5$ GeV $f_{K^*,\vert\vert} = 0.220 \pm 0.005$ GeV $\xi_\perp(0) = 0.31^{+0.20}_{-0.10}$ $a_{1,\vert\vert,\perp}(2\text{ GeV}) = 0.03 \pm 0.03$ $\lambda_B(\mu_h) = 0.51 \pm 0.12$ GeV	$f_B = 0.200 \pm 0.025$ GeV $f_{K^*,\perp}(2\text{ GeV}) = 0.163 \pm 0.008$ GeV $\xi_{\vert\vert}(0) = 0.10 \pm 0.03$ $a_{2,\vert\vert,\perp}(2\text{ GeV}) = 0.08 \pm 0.06$
$f_{B_s} = 0.2358 \pm 0.0089$ GeV	$\tau_{B_s} = 1.472 \pm 0.026$ ps

Inputs of the SM global fit

CKM fitter

CKM matrix within a frequentist framework ($\simeq \chi^2$ minimum)
+ specific scheme for theory errors (Rfit)

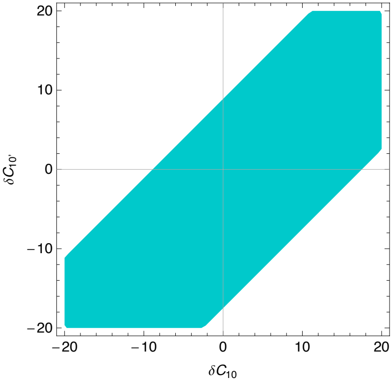
data = weak $\otimes$ QCD

$\Longrightarrow$Need for hadronic inputs (often lattice) with good theoretical control

$\vert V_{ud}\vert$	superallowed β decays	PRC79, 055502 (2009)
$\vert V_{us}\vert$	$K_{\ell 3}$ (Flavianet)	$f_+(0) = 0.963 \pm 0.003 \pm 0.005$
ϵ_K	PDG 08	$\hat{B}_K = 0.724 \pm 0.004 \pm 0.067$
$\vert V_{ub}\vert$	inclusive and exclusive	$\vert V_{ub}\vert \cdot 10^3 = 3.92 \pm 0.09 \pm 0.45$
$\vert V_{cb}\vert$	inclusive and exclusive	$\vert V_{cb}\vert \cdot 10^3 = 40.89 \pm 0.38 \pm 0.59$
Δm_d	last WA B_d-$\bar{B}_d$ mixing	$B_{B_s}/B_{B_d} = 1.01 \pm 0.01 \pm 0.03$
Δm_s	last WA B_s-$\bar{B}_s$ mixing	$B_{B_s} = 1.28 \pm 0.02 \pm 0.03$
β	last WA $J/\psi K^{(*)}$	
α	last WA $\pi\pi, \rho\pi, \rho\rho$	isospin
γ	last WA $B \to D^{(*)} K^{(*)}$	GLW/ADS/GGSZ
$B \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$	$f_{B_s}/f_{B_d} = 1.209 \pm 0.007 \pm 0.023$
		$f_{B_s} = 231 \pm 3 \pm 15$ MeV

Constraint on $C_{10}, C_{10'}$ from $B_s \to \mu^+\mu^-$

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-)|_{\rm axial} = \frac{G_F^2\alpha^2}{16\pi^3} f_{B_s}^2 m_{B_s}\tau_{B_s}|V_{tb}V_{ts}^*|^2 m_\mu^2\sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}|C_{10}-C_{10'}|^2$$



Using our inputs, we get

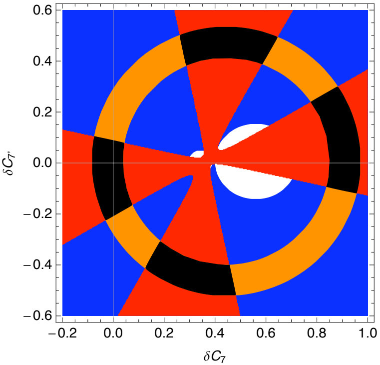
$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-)^{\rm SM} = (3.44 \pm 0.32)\cdot 10^{-9}$$

one order of magnitude smaller than 90% CL exp bound

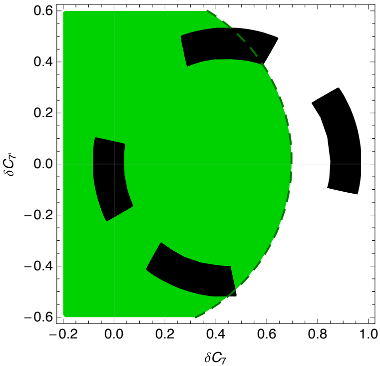
$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-)^{\rm exp} < 3.2 \cdot 10^{-8}.$$

and only weak constraints on $C_{10}, C_{10'}$

At two sigmas : $(C_7, C_{7'})$ and scenario A

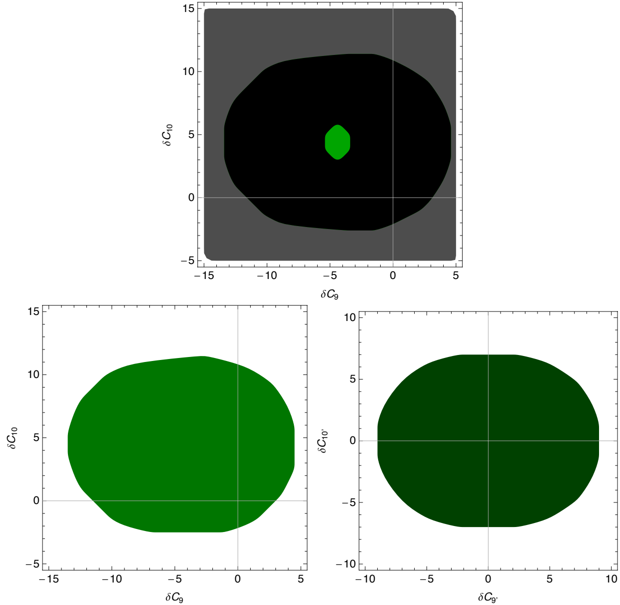


$(C_7, C_{7'})$ from class-I



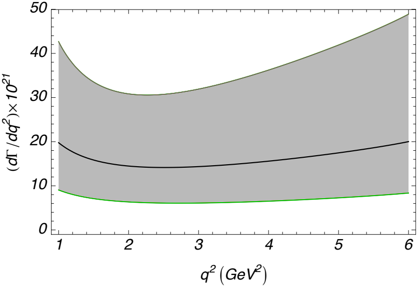
$B \to X_s \mu^+ \mu^-$ in scenario A

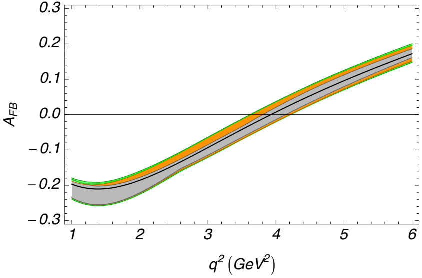
At two sigmas : scenario B and C



- Scenario B (up): $B \to X_s \mu^+ \mu^-$ and $\tilde{F}_L$
- Scenario C (down): $B \to X_s \mu^+ \mu^-$

SM prediction for $B \to K^* \ell^+ \ell^-$: $d\Gamma/dq^2$ and A_{FB}





Standard Model values

In the SM, NNLO in MS-bar with fully anticommuting γ_5 including electromagnetic corrections [Chetyrkin, Misiak and Münz, Huber et al.]

$C_1(\mu_b)$	$C_2(\mu_b)$	$C_3(\mu_b)$	$C_4(\mu_b)$	$C_5(\mu_b)$
-0.263	1.011	-0.006	-0.081	0.000
$C_6(\mu_b)$	$C_7^{\rm eff}(\mu_b)$	$C_8^{\rm eff}(\mu_b)$	$C_9(\mu_b)$	$C_{10}(\mu_b)$
0.001	-0.292	-0.166	4.075	-4.308

- High-scale $\mu_0 = 2M_W$ [uncertainty: varied from M_W to $4M_W$]
- Low-scale $\mu_b = 4.8$ GeV [uncertainty: varied from 2.4 to 9.6 GeV]

For the chirally-flipped operators, we have the SM values

$$C_{7'}^{SM} = \frac{m_s}{m_b} C_7^{SM}, \qquad C_{9',10'}^{SM} = 0$$

Form factors for $B \to K^*\gamma$

- full q^2-range using light-cone sum rules
- large recoil for NLO QCD factorisation with soft form factors $\xi_{\perp,||}$ + hard gluon corrections (+ 10% Λ/m_b corrections)

$\Longrightarrow$we use the latter to treat exclusive observables for q^2=1-6 GeV^2, extracting 2 soft form factors from LCSR determinations

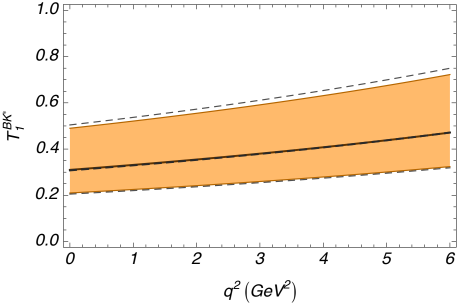
$$\xi_\perp(q^2) = \frac{m_B}{m_B+m_{K^*}} V(q^2), \quad \xi_{||}(q^2) = \frac{m_B+m_{K^*}}{2E_{K^*}} A_1(q^2) - \frac{m_B-m_{K^*}}{m_B} A_2(q^2)$$

Form factors for $B \to K^*\gamma$

- full q^2-range using light-cone sum rules
- large recoil for NLO QCD factorisation with soft form factors $\xi_{\perp,||}$ + hard gluon corrections (+ 10% Λ/m_b corrections)

$\Longrightarrow$we use the latter to treat exclusive observables for q^2=1-6 GeV^2, extracting 2 soft form factors from LCSR determinations

$$\xi_\perp(q^2) = \frac{m_B}{m_B+m_{K^*}} V(q^2), \quad \xi_{||}(q^2) = \frac{m_B+m_{K^*}}{2E_{K^*}} A_1(q^2) - \frac{m_B-m_{K^*}}{m_B} A_2(q^2)$$



5 other form factors then consistent, e.g. $T_1^{B\to K^*}$

- orange : full form factor from LCSR [Khodjamirian et al]
- grey lines : NLO QCD factorisation [Beneke et al.] using our $\xi_\perp(q^2)$

Class-I observables: inclusive $\mathcal{B}(\bar{B} \to X_s\gamma)$

Class-I : only depending on $C_7, C_{7'}$, related to radiative decays

[Misiak, Gambino, Steinhauser. . .]

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{exp}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$$

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{th}_{E_\gamma > 1.6\,\mathrm{GeV}} = \Big[a_{(0,0)} + a_{(7,7)} \left[(\delta C_7)^2 + (\delta C_{7'})^2\right] + +a_{(0,7)}\, \delta C_7 + a_{(0,7')}\, \delta C_{7'}\Big] \times 10^{-4}$$

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{SM}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$

Class-I observables: inclusive $\mathcal{B}(\bar{B} \to X_s\gamma)$

Class-I : only depending on $C_7, C_{7'}$, related to radiative decays

[Misiak, Gambino, Steinhauser. . .]

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{exp}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$$

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{th}_{E_\gamma > 1.6\,\mathrm{GeV}} = \Big[a_{(0,0)} + a_{(7,7)} \left[(\delta C_7)^2 + (\delta C_{7'})^2\right] + +a_{(0,7)}\,\delta C_7 + a_{(0,7')}\,\delta C_{7'}\Big] \times 10^{-4}$$

$$\mathcal{B}(\bar{B} \to X_s\gamma)^{SM}_{E_\gamma > 1.6\,\mathrm{GeV}} = (3.15 \pm 0.23) \times 10^{-4}$$

- SM value $[a_{(0,0)}]$ expressed as

$$\mathcal{B}(B \to X_s\gamma)^{SM}_{E_\gamma > E_0} = \mathcal{B}(B \to X_c e\bar{\nu}) \left|\frac{V^*_{ts}V_{tb}}{V_{cb}}\right|^2 \frac{6\alpha_{\rm em}}{\pi}[P(E_0) + N(E_0)]$$

$$P(E_0) = \sum_{i,j=1\ldots 8} C_i^{\rm eff}(\mu) C_j^{\rm eff*}(\mu) K_{ij}(E_0, \mu)$$

- left- and right-handed polarisations add up incoherently
  - $a_{(7,7)} = a_{(7',7')}$ same structure for C_7 and $C_{7'}$ $\gamma_5 \to -\gamma_5$
  - $a_{(0,7)} \neq a_{(0,7')}$ since no 4-quark chirally flipped operators
- numerical a's reproducing [Misiak, Steinhauser, Haisch]

Class-I observables: isospin asymmetry in $B \to K^*\gamma$

[Kagan and Neubert. . .]

$$A_I(B \to K^*\gamma) = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

- NLO QCD factorisation : isospin asymmetry from nonfactorisable contributions where spectator quark emits the photon
- from 4-quark and chromomagnetic operators
- thus no change once chirally-flipped operators included, apart from normalisation to isospin-averaged branching ratio

Class-I observables: isospin asymmetry in $B \to K^*\gamma$

[Kagan and Neubert…]

$$A_I(B \to K^*\gamma) = \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

- NLO QCD factorisation : isospin asymmetry from nonfactorisable contributions where spectator quark emits the photon
- from 4-quark and chromomagnetic operators
- thus no change once chirally-flipped operators included, apart from normalisation to isospin-averaged branching ratio

$$\begin{aligned} A_I(B \to K^*\gamma)^{exp} &= 0.052 \pm 0.026 \\ A_I(B \to K^*\gamma)^{th} &= c \times \frac{\sum_k d_k (\delta C_7)^k}{\sum_{k,l} e_{k,l} (\delta C_7)^k (\delta C_{7'})^l} \pm \delta c\,. \\ A_I(B \to K^*\gamma)^{SM} &= 0.041 \pm 0.025 \end{aligned}$$

- c, d, e determined numerically,

  reproducing [Kagan and Neubert, Feldmann and Matias]

Class-I observables: $B \to K^*\gamma$ CP-asymmetry

[Beneke Feldmann Seidel, Ball and Zwicky]

$$\frac{\Gamma(\bar{B}^0(t)\to\bar{K}^{*0}\gamma)-\Gamma(B^0(t)\to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t)\to\bar{K}^{*0}\gamma)+\Gamma(B^0(t)\to K^{*0}\gamma)} = S_{K^*\gamma}\sin(\Delta m_B t) - C_{K^*\gamma}\cos(\Delta m_B t)$$

- Probe of photon helicity $S_{K^*\gamma} = \frac{2\,\mathrm{Im}\left[e^{-2i\beta}\left(\mathcal{A}_L^*\bar{\mathcal{A}}_L + \mathcal{A}_R^*\bar{\mathcal{A}}_R\right)\right]}{|\mathcal{A}_L|^2+|\mathcal{A}_R|^2+|\bar{\mathcal{A}}_L|^2+|\bar{\mathcal{A}}_R|^2}$
- Cam be determined at NLO in QCD factorisation. At LO,

$$S_{K^*\gamma}^{(\mathrm{LO})} = \frac{-2\left|C_{7'}/C_7\right|}{1+\left|C_{7'}/C_7\right|^2}\sin\left(2\beta - \arg\left(C_7 C_{7'}\right)\right)$$

[Grinstein et al, Bobeth et al]

Class-I observables: $B \to K^*\gamma$ CP-asymmetry

[Beneke Feldmann Seidel, Ball and Zwicky]

$$\frac{\Gamma(\bar{B}^0(t)\to\bar{K}^{*0}\gamma)-\Gamma(B^0(t)\to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t)\to\bar{K}^{*0}\gamma)+\Gamma(B^0(t)\to K^{*0}\gamma)} = S_{K^*\gamma}\sin(\Delta m_B t) - C_{K^*\gamma}\cos(\Delta m_B t)$$

- Probe of photon helicity $S_{K^*\gamma} = \frac{2\,\mathrm{Im}\left[e^{-2i\beta}\left(\mathcal{A}_L^*\bar{\mathcal{A}}_L + \mathcal{A}_R^*\bar{\mathcal{A}}_R\right)\right]}{|\mathcal{A}_L|^2+|\mathcal{A}_R|^2+|\bar{\mathcal{A}}_L|^2+|\bar{\mathcal{A}}_R|^2}$
- Cam be determined at NLO in QCD factorisation. At LO,

$$S^{(\mathrm{LO})}_{K^*\gamma} = \frac{-2\left|C_{7'}/C_7\right|}{1+\left|C_{7'}/C_7\right|^2}\sin\left(2\beta - \arg\left(C_7 C_{7'}\right)\right)$$

[Grinstein et al, Bobeth et al]

$$\begin{aligned} S^{\mathrm{exp}}_{K^*\gamma} &= -0.16 \pm 0.22 \\ S_{K^*\gamma} &= f\,{}^{+\delta_f^u}_{-\delta_f^d} + \frac{\sum_{k,l} g_{k,l}(\delta C_7)^k(\delta C_{7'})^l}{\sum_{k,l} h_{k,l}(\delta C_7)^k(\delta C_{7'})^l} \\ S^{SM}_{K^*\gamma} &= -0.30 \pm 0.01 \end{aligned}$$

- f, g, h fitting coefficients and uncertainties determined numerically

Class-II observables: A_T^2 asymmetry

Class-II : depending only on dipole and semileptonic operators

$B \to K^* \ell^+ \ell^-$ asymmetry $A_T^2(q^2) = \frac{|A_\perp|^2 - |A_\||^2}{|A_\perp|^2 + |A_\||^2}$, [Kruger and Matias]

- $B \to K^* \ell^+ \ell^-$ expressed in terms of 7 spin amplitudes
- $A_\perp$ and $A_\|$ depend only on $C_{7,7',9,9',10,10'}$ (no tensors or scalars)
- can be determined from $d\Gamma/d\phi$
- weakly sensitive to soft form factors (only at NLO QCDF)
- not measured yet, but potential to discriminate among scenarios

Class-II observables: A_T^2 asymmetry

Class-II : depending only on dipole and semileptonic operators

$B \to K^*\ell^+\ell^-$ asymmetry $A_T^2(q^2) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$, [Kruger and Matias]

- $B \to K^*\ell^+\ell^-$ expressed in terms of 7 spin amplitudes
- $A_\perp$ and $A_\parallel$ depend only on $C_{7,7',9,9',10,10'}$ (no tensors or scalars)
- can be determined from $d\Gamma/d\phi$
- weakly sensitive to soft form factors (only at NLO QCDF)
- not measured yet, but potential to discriminate among scenarios

At low q^2, at NLO QCD factorisation $A_T^2(q^2) = A_{\mathrm{T}}^{(2),\,CV}(q^2)^{+\delta_u(q^2)}_{-\delta_d(q^2)}$
with fitting q^2-polynomials for errors δ_u, δ_d and central value

$$A_T^{(2),\,CV}(q^2) = \frac{\sum_{i=0,7,7',9,9',10,10'} \sum_{j=i,..10'} F_{(i,j)}(q^2)\delta C_i \delta C_j}{\sum_{i=0,7,7',9,9',10,10'} \sum_{j=i,..10'} G_{(i,j)}(q^2)\delta C_i \delta C_j}$$

[$\delta C_0 = 1$ to deal with constant, linear and quadratic terms]

Class-III observables: $\bar{B} \to X_s \mu^+ \mu^-$

Class-III: depending on dipole and semileptonic operators, but also others (scalar, tensors) $\Longrightarrow$ most of semileptonic observables

- $\bar{B} \to X_s \mu^+ \mu^-$ at low q^2 [1-6 GeV^2]

$$\begin{aligned}
\mathcal{B}(\bar{B} \to X_s \mu^+ \mu^-)^{exp} &= (1.60 \pm 0.50) \times 10^{-6} \\
\mathcal{B}(B \to X_s \mu^+ \mu^-) &= 10^{-7} \times \sum_{i,j=0,7,7',9,9',10,10'} b_{(i,j)} \delta C_i \delta C_j \\
\mathcal{B}(\bar{B} \to X_s \mu^+ \mu^-)^{SM} &= (1.59 \pm 0.15) \times 10^{-6}
\end{aligned}$$

  - $\delta C_7, \delta C_9, \delta C_{10}$-only contributions known up to NNLO including e.m. corrections [Huber et al]
  - $\delta C_{7'}, \delta C_{9'}, \delta C_{10'}$-only contributions with similar structure ($\gamma_5 \to -\gamma_5$)
  - crossed terms (primed-unprimed) only at LO in α_s, and are suppressed by m_s/m_b [Guetta Nardi]
  - b coefficients determined numerically agreeing with [Huber et al]

Class-III observables: $\tilde{A}_{\mathrm{F}B}$ and $\tilde{F}_L$

Average forward-backward asymmetry $\tilde{A}_{\mathrm{F}B}$
and longitudinal polarisation $\tilde{F}_L$ over low q^2 =1-6 GeV^2

$$\frac{dA_{\mathrm{FB}}}{dq^2} = \left(\int_0^1 d(\cos\theta_l)\frac{d^2\Gamma}{dq^2 d\cos\theta_l} - \int_{-1}^0 \dots\right) / \frac{d\Gamma}{dq^2} \qquad F_{\mathrm{L}} = |A_0|^2 / \frac{d\Gamma}{dq^2}$$

Class-III observables: $\tilde{A}_{\mathrm{FB}}$ and $\tilde{F}_L$

Average forward-backward asymmetry $\tilde{A}_{\mathrm{FB}}$
and longitudinal polarisation $\tilde{F}_L$ over low q^2 =1-6 GeV^2

$$\frac{dA_{\mathrm{FB}}}{dq^2} = \left(\int_0^1 d(\cos\theta_l)\frac{d^2\Gamma}{dq^2 d\cos\theta_l} - \int_{-1}^0 \dots\right) / \frac{d\Gamma}{dq^2} \qquad F_{\mathrm{L}} = |A_0|^2 / \frac{d\Gamma}{dq^2}$$

$$\tilde{A}_{FB}^{\mathrm{exp}} = 0.33^{+0.22}_{-0.24} \qquad \tilde{F}_L^{\mathrm{exp}} = 0.60^{+0.18}_{-0.19}$$

$$\tilde{A}_{FB} = \frac{\int_{1\mathrm{GeV}^2}^{6\mathrm{GeV}^2} \sum_{i=0,7,7',9,9',10,10'} \sum_{j=i,..10'} H_{(i,j)}(q^2)\delta C_i \delta C_j dq^2}{\int_{1\mathrm{GeV}^2}^{6\mathrm{GeV}^2} \sum_{i=0,7,7',9,9',10,10'} \sum_{j=i,..10'} I_{(i,j)}(q^2)\delta C_i \delta C_j dq^2} {}^{+\tilde{\delta}_u}_{-\tilde{\delta}_d}$$

computed at NLO in QCD factorisation [Beneke and Feldmann]
with fitting q^2-polynomials for central value and errors (same for $\tilde{F}_L$)

$$\tilde{A}_{FB}^{SM} = 0.022^{+0.028}_{-0.028} \qquad \tilde{F}_L^{SM} = 0.732^{+0.021}_{-0.031}$$