C1b: $B - \bar{B}$ mixing, CP violation, and Lifetimes

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SFB meeting
Siegen, 7 Oct 2020

Teams

KIT-Yerevan:

H.M. Asatrian, A. Hovhannisyan, UN, A. Yeghiazaryan,
JHEP 1710 (2017) 191

H.M. Asatrian, H.H. Asatryan, A. Hovhannisyan, S. Tumasyan, UN, A. Yeghiazaryan, Phys.Rev. D102 (2020) no.3, 033007

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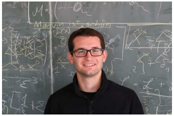
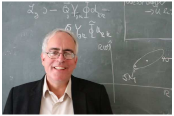
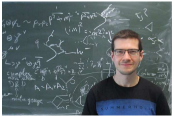
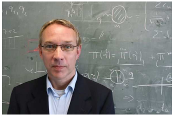





Contents

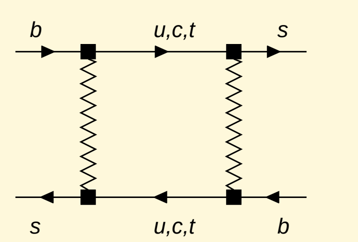
B_s–$\bar{B}_s$ mixing

B_s–$\bar{B}_s$ mixing involves the 2×2 matrices M^s and Γ^s, calculated from the box diagram.

Diagonalise $M^s - i\,\frac{\Gamma^s}{2}$ to find the two mass eigenstates:

$$\begin{aligned} |B_L\rangle &= p|B_s\rangle + q|\bar{B}_s\rangle. \\ |B_H\rangle &= p|B_s\rangle - q|\bar{B}_s\rangle \end{aligned}$$

with masses $M^s_{L,H}$ and widths $\Gamma^s_{L,H}$.



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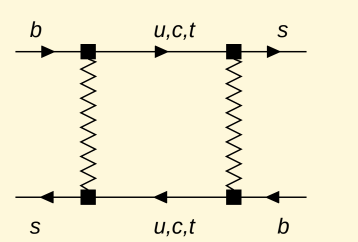

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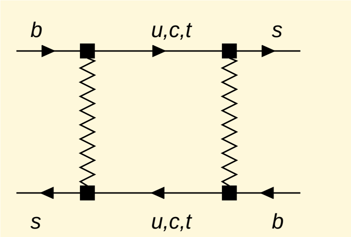
Mass and width differences:

$$
\begin{aligned}
\Delta m_s &= M_H - M_L \simeq 2|M^s_{12}|, \\
\Delta\Gamma_s &= \Gamma_L - \Gamma_H \simeq 2|\Gamma^s_{12}|\cos\phi^{(s)}
\end{aligned}
$$

where

$$
\begin{aligned}
\phi^{(s)} &\equiv \arg\left(-\frac{M^s_{12}}{\Gamma^s_{12}}\right) \\
&\sim 0
\end{aligned}
$$

Δm_s equals the oscillation frequency between B_s and $\bar{B}_s$ and involves the $(1,2)$ element of the mass matrix M^s.
It is calculated from the dispersive part of the box diagram, which is dominated by virtual t quarks.



The width difference $\Delta\Gamma_s$ involves the decay matrix Γ^s and stems from the absorptive part of the box diagram, involving the light u,c quarks on the internal lines.

Theoretical predictions for Δm_s and $\Delta\Gamma_s$ are sums of terms looking like

$$|V_{tb} V_{ts}|^2 \times \text{perturbative coefficient} \times \text{hadronic matrix element}$$

$|V_{ts}| \simeq |V_{cb}|$ introduces a parametric uncertainty

The perturbative uncertainty can be systematically reduced by calculating higher orders in α_s.

Matrix elements like $\langle B_s | \bar{s}\gamma^\mu(1-\gamma_5)b \, \bar{s}\gamma^\mu(1-\gamma_5)b | \overline{B}_s \rangle$ are calculated with lattice QCD or QCD sum rules and are sources of hadronic uncertainty.

Δm_s probes new physics from virtual particles with masses beyond 100 TeV.
$\Delta\Gamma_s$ is essentially insensitive to new physics, except for new $\bar{b}s\bar{c}c$ interactions.

S. Jäger, M. Kirk, A. Lenz, K. Leslie, Phys.Rev. D97 (2018) 015021

Experiment (CDF, LHCb):

$$\Delta m_s^{\rm exp} = (17.757 \pm 0.021)\,\mathrm{ps}^{-1}$$

Theory prediction:

$$\Delta m_s = (17.4\ {}^{+0.2}_{-0.6}{}_{|V_{ts}|} \pm 0.7_{\rm had})\,\mathrm{ps}^{-1}$$

Perturbative uncertainties are smaller. $|V_{ts}|$ is taken from CKMfitter (which, however, uses Δm_s as input to its global fit).

Mistakes in hadronic calculations can mimick new physics in Δm_s. The $|V_{cb}|$ controversy feeds into $|V_{ts}|$ and limits the precision of the Δm_s prediction.

But: Information from $\Delta\Gamma_s$ can distinguish new physics from hadronic and parametric uncertainties.

Mistakes in hadronic calculations can mimick new physics in Δm_s. The $|V_{cb}|$ controversy feeds into $|V_{ts}|$ and limits the precision of the Δm_s prediction.

But: Information from $\Delta\Gamma_s$ can distinguish new physics from hadronic and parametric uncertainties.

$|V_{ts}|$ and most of the hadronic uncertainty drops out from $\dfrac{\Delta\Gamma_s}{\Delta m_s}$:

If $\dfrac{\Delta\Gamma_s^{\rm exp}}{\Delta m_s^{\rm exp}}$ agrees with the SM prediction, there is no new physics in Δm_s. Any potential discrepancy in Δm_s would then be due to $|V_{ts}| \simeq |V_{cb}|$ or incorrect assessments of hadronic uncertainty.

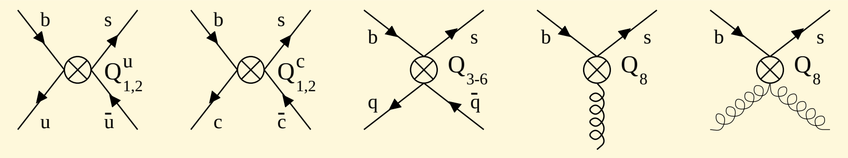
Effective hamiltonian

$$H^{|\Delta B|=1} = \frac{G_F}{\sqrt{2}} \left[\sum_{i=1}^{2} C_i \left(V_{ub} V_{us}^* Q_i^u + V_{cb} V_{cs}^* Q_i^c \right) + V_{tb} V_{ts}^* \sum_{i \geq 3} C_i Q_i \right]$$

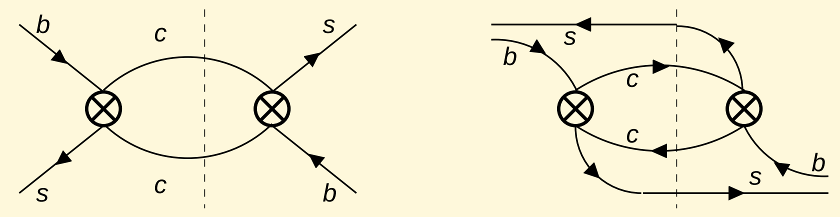
Q_i: effective $|\Delta B| = 1$ operators, e.g. $Q_2^c = \overline{c}\gamma_\mu(1-\gamma_5)b\ \overline{d}\gamma^\mu(1-\gamma_5)c$

C_i: Wilson coefficients = effective couplings, contain short distance structure including QCD corrections, depend on $\frac{m_t}{M_W}$.

$Q_{3-6,8}$ are penguin operators

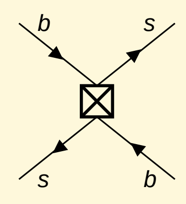


Leading contribution to $\Delta\Gamma_s$:



$\Delta\Gamma_s$ stems from Cabibbo-favoured tree-level $b \to c\bar{c}s$ decays.

Heavy Quark Expansion (HQE):
Exploit $m_b \gg \Lambda_{QCD}$ to express $\Delta\Gamma_s$ in terms of short-distance coefficients and matrix elements of local $|\Delta B| = 2$ operators.



$\Rightarrow$ expansion of $\Delta\Gamma_s$ in $\alpha_s(m_b)$ and Λ_{QCD}/m_b.

Operators at leading order in Λ_{QCD}/m_b (leading power):

$$Q = \bar{s}_i \gamma_\mu (1-\gamma_5) b_i \; \bar{s}_j \gamma^\mu (1-\gamma_5) b_j, \qquad \widetilde{Q}_S = \bar{s}_i (1+\gamma_5) b_j \; \bar{s}_j (1+\gamma_5) b_i.$$

i, j are colour indices.

Matrix elements:

$$\langle B_s | Q | \overline{B}_s \rangle = \frac{8}{3} M_{B_s}^2 \, f_{B_s}^2 \, B$$

$$\langle B_s | \widetilde{Q}_S | \overline{B}_s \rangle \; = \; \frac{1}{3} M_{B_s}^2 \, f_{B_s}^2 \, \widetilde{B}'_S.$$

Here $f_{B_s} = (0.2307 \pm 0.0013)\,\text{GeV}$ is the B_s decay constant and $M_{B_s} = 5.37\,\text{GeV}$ is the B_s mass. In the $\overline{\text{MS}}$ scheme:

$$B = 0.813 \pm 0.034 \qquad \text{and} \qquad \widetilde{B}'_S = 1.31 \pm 0.09.$$

The HQE gives

$$\Delta\Gamma_s = \frac{G_F^2 m_b^2}{12\pi M_{B_s}} |V_{cs}^* V_{cb}|^2 \left| G' \langle B_s|Q|\bar{B}_s\rangle + \widetilde{G}_S \langle B_s|\widetilde{Q}_S|\bar{B}_s\rangle \right|$$

with the perturbative coefficients $G', \widetilde{G}_S$.

The coefficients $G', \widetilde{G}_S$ emerging from the calculation correspond to the choice $m_b = m_b^{\text{pole}}$ in the prefactor. Subsequently one may switch to the $\overline{\text{MS}}$ definition $\bar{m}_b$ through e.g.

$$\widetilde{G}_S^{\overline{\text{MS}}} \equiv \frac{m_b^{\text{pole}\,2}}{\bar{m}_b^2} \widetilde{G}_S$$

and expanding in α_s to the order in which $G', \widetilde{G}_S$ are calculated.

Experiment (HFLAV 2019): $\Delta\Gamma^{\exp} = (0.089 \pm 0.006)\,\mathrm{ps}^{-1}$
average from LHCb, ATLAS, CMS, and CDF data.

Theory prediction with QCD corrections at next-to-leading order (NLO):

$$\Delta\Gamma_s = \left(0.077 \pm 0.015_{\rm pert} \pm 0.002_{B,\widetilde{B}_S} \pm 0.017_{\Lambda_{QCD}/m_b}\right)\ \mathrm{GeV} \qquad \text{(pole)}$$

$$\Delta\Gamma_s = \left(0.088 \pm 0.011_{\rm pert} \pm 0.002_{B,\widetilde{B}_S} \pm 0.014_{\Lambda_{QCD}/m_b}\right)\ \mathrm{GeV} \qquad (\overline{\rm MS})$$

H.M. Asatrian, H.H. Asatryan, A. Hovhannisyan, S. Tumasyan, UN,
A. Yeghiazaryan, Phys.Rev. D102 (2020) no.3, 033007

based on the NLO calculations in

M. Beneke, G. Buchalla, C. Greub, A. Lenz, UN, PLB459 (1999) 631
A. Lenz, UN, JHEP 0706 (2007) 072

The perturbative error exceeds the experimental error.
$\Rightarrow$ need NNLO!

NNLO

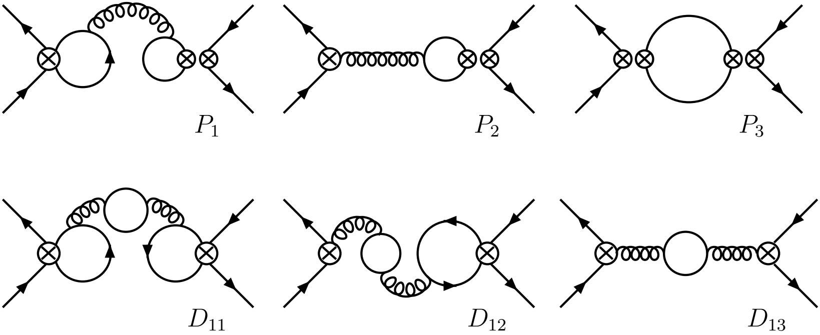
The NNLO calculation involves propagator-type three-loop diagrams with the two masses m_c and m_b.

First step: diagrams with closed fermion loop (large-N_f limit) and neglecting $\mathcal{O}(m_c^2/m_b^2)$ terms.

H.M. Asatrian, A. Hovhannisyan, A. Yeghiazaryan, UN,
JHEP 1710 (2017) 191

Second step: NNLO penguin effects diagrams with closed fermion loop (large-N_f limit) and exact m_c dependence.

H.M. Asatrian, H.H. Asatryan, A. Hovhannisyan, S. Tumasyan, UN,
A. Yeghiazaryan, Phys.Rev. D102 (2020) no.3, 033007.



The penguin coefficients $C_{3-6} = \mathcal{O}(0.05)$ are counted as α_s.

The new penguin contributions to Γ_{12}^s constitute a numerically insignificant contribution to $\Delta\Gamma_s$. A conceptually important result is the absence of terms proportional to $m_c^2 \log \frac{m_c^2}{m_b^2}$. This is expected on the basis that there are no dim-8 operators with two charm fields. $\Rightarrow$ test of the concept
Also: $\frac{m_c^2}{m_b^2}$ corrections have a large coefficient, increasing the partial NNLO penguin contributions by 14%.

However, the new large-N_f penguin contributions are the first step towards the NNLO prediction of the CP asymmetries in flavour-specific (typically semi-leptonic) decays:

$$a_{\text{fs}}^q = \frac{\Gamma(\bar{B}_q(t) \to f) - \Gamma(B_q(t) \to \bar{f})}{\Gamma(\bar{B}_q(t) \to f) + \Gamma(B_q(t) \to \bar{f})} \qquad \text{with} \quad q = d, s$$

$$a_{\rm fs}^{s,\exp} = (60 \pm 280) \cdot 10^{-5}$$

from semi-leptonic decays.

NLO update:

$$\begin{aligned} a_{\rm fs}^{s} &= (2.07 \pm 0.08_{\rm pert} \pm 0.02_{B,\widetilde{B}_S} \pm 0.05_{\Lambda_{QCD}/m_b} \\ &\quad \pm 0.04_{\rm CKM}) \times 10^{-5} \ \ ({\rm pole}), \\ a_{\rm fs}^{s} &= (2.04 \pm 0.09_{\rm pert} \pm 0.02_{B,\widetilde{B}_S} \pm 0.04_{\Lambda_{QCD}/m_b} \\ &\quad \pm 0.04_{\rm CKM}) \times 10^{-5} \ \ (\overline{\rm MS}), \end{aligned}$$

H.M. Asatrian, H.H. Asatryan, A. Hovhannisyan, S. Tumasyan, UN, A. Yeghiazaryan, Phys.Rev. D102 (2020) no.3, 033007

based on the NLO calculations in

M. Beneke, G. Buchalla, A. Lenz, UN, PLB576 (2003) 173

A. Lenz, UN, JHEP 0706 (2007) 072

$$a_{\rm fs}^{d,\rm exp} = (-21 \pm 17) \cdot 10^{-4}$$

from semi-leptonic decays.

NLO update:

$$\begin{aligned} a_{\rm fs}^{d} &= -(4.71 \pm 0.18_{\rm pert} \pm 0.04_{B,\widetilde{B}_S} \pm 0.11_{\Lambda_{QCD}/m_b} \\ &\quad \pm 0.10_{\rm CKM}) \times 10^{-4} \quad ({\rm pole}), \\ a_{\rm fs}^{d} &= -(4.64 \pm 0.21_{\rm pert} \pm 0.04_{B,\widetilde{B}_S} \pm 0.09_{\Lambda_{QCD}/m_b} \\ &\quad \pm 0.10_{\rm CKM}) \times 10^{-4} \quad (\overline{\rm MS}). \end{aligned}$$

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A. Lenz, UN, JHEP 0706 (2007) 072

Outlook

The large-N_f pieces of the NNLO corrections to Γ_{12}^q do not improve the predictions of $\Delta\Gamma_{d,s}$ and $a_{\mathrm{fs}}^{d,s}$.

The full NNLO calculation of Γ_{12}^q in project C1b is in progress. Intermediate results are

- verification of the NLO results in a different operator basis
- NNLO penguin results beyond the large-N_f limit
- first results of 3-loop master integrals for $m_c = 0$