On New Physics at tree level in hadronic $B$ meson decays and the determination of the CKM angle $\gamma$

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Why new Physics at Tree Level?

- Based on the data available there is plenty of room for deviations from the Standard Model (SM).

- New Physics (NP) effects in semileptonic tree level transitions $b \rightarrow c l \nu$:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)}$$

BABAR + LHCb + Belle combination 3.9 $\sigma$ deviation with respect to the SM.

Amhis et al. (2016), arXiv:1612.07233 [hep-ex]

- NP effects in semileptonic tree level transitions $b \rightarrow u l \nu$:

By considering different ratios between the branching fractions for the processes:

$$B^- \rightarrow \mu^- \bar{\nu}_\mu, \quad B^- \rightarrow \tau^- \bar{\nu}_\tau, \quad \bar{B} \rightarrow \pi \ell \bar{\nu}_\ell, \quad \bar{B} \rightarrow \rho \ell \bar{\nu}_\ell$$

it is found that there is plenty of room for NP scalar and pseudoscalar interactions.

arXiv:1809.09051 [hep-ph]
We want to explore the possibility of having NP in the non-leptonic processes:

\[ b \rightarrow u\bar{u}d \quad b \rightarrow u\bar{c}d \quad b \rightarrow c\bar{u}d \quad b \rightarrow c\bar{c}d \quad (d \rightarrow s). \]

In the SM these processes proceed at tree level.
New Physics at tree level in non-leptonic $B$ decays

The possibility of having NP at tree level in hadronic $B$ decays has been considered before to:

- **Address the 2010 $D_0$ dimuon asymmetry**

- **Evaluate enhancements in the $B^0_d$ observable $\Delta \Gamma_d$**

- **Investigate the $\Delta A_{CP}$ puzzle in $B \rightarrow K\pi$ decays**

- **Evaluate the impact on the determination of the CKM angle $\gamma$**

However none of these studies has been complete or has accounted properly for the uncertainties due to non-factorizable hadronic contributions.
Effective field theory formalism

We have followed an effective theory approach

\[
\hat{Q}_1 = \left( \bar{c}_\alpha b_\beta \right)_{V-A} \left( \bar{d}_\beta u_\alpha \right)_{V-A}
\]
\[
\hat{Q}_2 = \left( \bar{c}_\alpha b_\alpha \right)_{V-A} \left( \bar{d}_\beta u_\beta \right)_{V-A}
\]

In the SM tree level interactions are described by two effective operators

The tree level effective Hamiltonian is

\[
\mathcal{H}_{\text{Tree}}^{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p,p'=u,c} \lambda_{pp'}^d \left( C_{i}^{pp'} (\mu) \hat{Q}_1^{pp'} + C_{i}^{pp'} (\mu) \hat{Q}_2^{pp'} \right)
\]
\[
\lambda_{pp'}^d = V_{pb} V_{p'd}^*
\]

In the SM at NLO

\[
C_1(m_b) \sim -0.19 \quad C_2(m_b) \sim 1.08
\]
Although we are interested in NP at tree level our computations involve other topologies.

The full effective Hamiltonian used during our computations is given by

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left( \sum_{p,p'=u,c} \lambda_{pp'}^d \sum_{i=1,2} C_{ij}^{pp'} (\mu) \hat{Q}_i^{pp'} \right)$$
Although we are interested in NP at tree level our computations involve other topologies.

The full effective Hamiltonian used during our computations is given by

\[
H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left( \sum_{p,p'=u,c} \lambda_{pp'}^d \sum_{i=1,2} C_i^{pp'}(\mu) \hat{Q}_i^{pp'} + \sum_{p=u,c} \lambda_p^d \left[ \sum_{i=3}^{10} C_i(\mu) \hat{Q}_i^P + C_{7\gamma} \hat{Q}_{7\gamma} + C_{8g} \hat{Q}_{8g} \right] \right) + h.c.,
\]

where \( \hat{Q}_i \) are operators representing different effects such as QCD penguins, electro-weak penguins, electromagnetic operator, and chromomagnetic operator.
Effective field theory formalism

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The full effective Hamiltonian used during our computations is given by

\[ \mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left( \sum_{p,p'=u,c} \lambda^d_{pp'} \sum_{i=1,2} C^p_{ip} (\mu) \hat{Q}^p_{ii} \right. \\
+ \sum_{p=u,c} \lambda^d_p \left[ \sum_{i=3}^{10} C_{ip} (\mu) \hat{Q}_i^p + C_{7\gamma} \hat{Q}_{7\gamma} + C_{8g} \hat{Q}_{8g} \right] \right) + h.c., \]

\[ \lambda^d_p = V_{pb} V^*_{pd} \]

\[ \hat{Q}_{1}^{pp'} - \hat{Q}_{2}^{pp'} : \text{Tree level.} \]

\[ \hat{Q}_3 - \hat{Q}_6 : \text{QCD Penguins.} \quad \hat{Q}_7 - \hat{Q}_{10} : \text{Electro-weak Penguins.} \]

\[ \hat{Q}_{7\gamma} : \text{Electromagnetic operator.} \quad \hat{Q}_{7g} : \text{Chromomagnetic operator.} \]
Introducing NP effects at tree level

The NP effects are introduced at the matching scale $M_W$

$$C_{1,2}(M_W) = C_{1,2}^{SM}(M_W) + \Delta C_{1,2}^{NP}(M_W).$$

To assess the size of $\Delta C_{1,2}^{NP}$ we perform a $\chi^2$-squared fit.

To implement the fit we use the software MyFitter


$$\chi^2(\vec{\omega}) = \sum_i \left( \frac{\hat{O}_{i,\text{exp}} - \hat{O}_{i,\text{theo}}(\vec{\omega})}{\sigma_{i,\text{exp}}} \right)^2$$

$$\vec{\omega} = (\Delta C_1^{NP}(M_W), \Delta C_2^{NP}(M_W); \vec{\lambda}_{\text{nuisance}})$$

Our nuisance parameters include CKM elements, decay constants, form factors, masses, etc:

$$\vec{\lambda}_{\text{nuisance}} = |V_{ub}/V_{cb}|, |V_{us}|, \mu, f_\pi, F_{B \to \pi}^+, ...,$$ etc
Introducing NP effects at tree level

Due to the non-diagonal nature of the anomalous dimension matrices, when solving the R.G.E.

\[ \mu \frac{d \bar{\mathcal{C}}}{d \mu} = \hat{\gamma}^T \bar{\mathcal{C}}. \]

the NP effects propagate to the other Wilson coefficients as well

\[ \bar{\mathcal{C}}(\mu) = \hat{U}(\mu, \mu_W, \hat{\gamma}, \alpha_s, \alpha) \bar{\mathcal{C}}(M_W). \]

Our initial conditions for the Wilson coefficients include strong + electroweak effects at NLO

\[ \bar{\mathcal{C}}(M_W) = \bar{\mathcal{C}}^{(0)}(M_W) + \frac{\alpha_s(M_W)}{4\pi} \bar{\mathcal{C}}^{(1)}(M_W) \]

\[ + \frac{\alpha}{4\pi} \left[ \bar{\mathcal{C}}^{(0)}(M_W) + \frac{\alpha_s(M_W)}{4\pi} \bar{\mathcal{C}}^{(1)}(M_W) + \bar{R}_e^{(0)}(M_W) \right]. \]

Introducing NP effects at tree level

To probe for potential NP phases we assume that our Wilson coefficients are complex.

To obtain bounds on $\Delta C_{1NP}^1$ and $\Delta C_{2NP}^2$ we use:

- Branching fractions of hadronic processes.
- CP asymmetries

$$\mathcal{A}_f^{CP}(t) = \frac{d\Gamma[B_q^0 \to f](t)/dt - d\Gamma[\bar{B}_q^0 \to f](t)/dt}{d\Gamma[B_q^0 \to f](t)/dt + d\Gamma[\bar{B}_q^0 \to f](t)/dt} \approx S_f \sin \Delta M_q t - C_f \cos \Delta M_q t,$$

The mixed induced CP asymmetry $S_f$ allow us to constrain new weak phases.

$$S_f \equiv \frac{2I m(\lambda_f^q)}{1 + |\lambda_f^q|^2}, \quad \lambda_f^q := e^{-2i\beta} \frac{\bar{A}_f^q}{A_f^q}.$$

- Neutral $B$ Mixing observables
- Life-time ratios

The full $\chi^2$-fit takes up to 1 week on 100 cores in the IPPP cluster (Durham University, UK).

Current progress in the Nikhef Stoomboot cluster.
Observables considered

\[ b \rightarrow u\bar{d} \]

- **\( B \rightarrow \pi\pi \):**

\[
R_{\pi\pi} = \frac{\Gamma(B^- \rightarrow \pi^0\pi^-)}{d\Gamma(\bar{B}_d^0 \rightarrow \pi^+l^-\bar{\nu}_l)/dq^2|q^2=0}
\]

\[
S_{\pi\pi} = \frac{2Im\left(\frac{e^{-2i\beta} \bar{A}_{\pi^0\pi^-}}{A_{\pi^0\pi^-}}\right)}{1 + |\frac{\bar{A}_{\pi^0\pi^-}}{A_{\pi^0\pi^-}}|^2}
\]

- **\( B \rightarrow \rho\pi \):**

\[
S_{\rho\pi} = \frac{2Im\left(\frac{e^{-2i\beta} \bar{A}_{\rho\pi}}{A_{\rho\pi}}\right)}{1 + |\frac{\bar{A}_{\rho\pi}}{A_{\rho\pi}}|^2}
\]

- **\( B \rightarrow \rho\rho \):**

\[
R_{\rho\rho} = \mathcal{B}_r(B^- \rightarrow \rho^-\rho_L^0)/\mathcal{B}_r(\bar{B}_d^0 \rightarrow \rho_L^+\rho_L^-)
\]
Observables considered

**$b \to c\bar{c}d$**

- $B \to D^* \pi$

  $$R_{D^*\pi} = \frac{\Gamma(\bar{B}^0 \to D^{*+}\pi^-)}{d\Gamma(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)/dq^2|_{q^2=m^2}}$$

**$b \to c\bar{c}d$**

- $B \to X_d \gamma$

  $$\mathcal{B}_r(B \to X_d \gamma)$$

**$b \to c\bar{c}s$**

- $B \to X_s \gamma$

  $$\mathcal{B}_r(B \to X_s \gamma)$$

- $B \to J/\psi K$

  $$S_{\rho\pi} = \frac{2\text{Im}\left(e^{-2i\beta} \frac{\bar{A}_{J/\psi K}}{A_{J/\psi K}}\right)}{1 + \left|\frac{\bar{A}_{J/\psi K}}{A_{J/\psi K}}\right|^2}$$
**Life-time ratio:** $\tau_{B_s}/\tau_{B_d}$

**B-physics anomalies.**

NP in $\hat{Q}_1 = \left( \bar{c}_\alpha b_\beta \right)_{V-A} \left( \bar{s}_\beta c_\alpha \right)_{V-A}$ and $\hat{Q}_2 = \left( \bar{c}_\alpha b_\alpha \right)_{V-A} \left( \bar{s}_\beta c_\beta \right)_{V-A}$

can induce deviations in the Wilson coefficient of $\hat{Q}_9V = \frac{\alpha}{4\pi} \left( \bar{s}_L \gamma_{\mu} \hat{b}_L \right) \left( \bar{\ell} \gamma^{\mu} \hat{\ell} \right)$

\[
\Delta C_{9}^{\text{eff}} \bigg|_{\mu=m_b} = \left[ 8.48 \Delta C_1 + 1.96 \Delta C_2 \right] \bigg|_{\mu=M_W}.
\]

Observables considered

Using the results for complex $\Delta C_{9}^{\text{eff}}$ provided in


we obtain the following regions

![Graphs showing the regions for $\Delta C_{9}^{s,cc}$](image-url)
Constraints from neutral $B$ meson mixing

The dynamics of neutral $B$ meson mixing is obtained from the following equation

$$i \frac{d}{dt} \left( \begin{array}{c} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{array} \right) = \hat{H} \left( \begin{array}{c} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{array} \right).$$

$$\hat{H} = \begin{pmatrix} M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\ M^*_{12} - \frac{i}{2} \Gamma^*_{12} & M_{11} - \frac{i}{2} \Gamma_{11} \end{pmatrix},$$

In the basis where $\hat{H}$ is diagonal we have

$$i \frac{d}{dt} \left( \begin{array}{c} |B_H(t)\rangle \\ |B_L(t)\rangle \end{array} \right) = \begin{pmatrix} \lambda_H & 0 \\ 0 & \lambda_L \end{pmatrix} \left( \begin{array}{c} |B_H(t)\rangle \\ |B_L(t)\rangle \end{array} \right).$$
Constraints from neutral $B$ meson mixing

$$\lambda_H = M_H - \frac{i}{2} \Gamma_H \quad \lambda_L = M_L - \frac{i}{2} \Gamma_L.$$ 

Neutral $B$ mixing is described by two observables

$$\Delta M = M_H - M_L \quad \Delta \Gamma = \Gamma_L - \Gamma_H.$$ 

The insertion of two tree-level operators contributes to neutral $B$ mixing

- $a_{s1}^s = |\Gamma_{s1}^s|/|M_{s1}^s| \sin \phi_{s1}$: $b \to u\bar{u}s, b \to u\bar{c}s, b \to c\bar{c}s$
- $\Delta \Gamma_s$: $b \to u\bar{u}s, b \to u\bar{c}s, b \to c\bar{c}s$
- $a_{d1}^s$: $b \to u\bar{d}d, b \to u\bar{c}d, b \to c\bar{c}d$
QCD Factorization

We include different observables calculated through the QCD Factorization formalism:

\[ B \rightarrow \pi\pi, \rho\pi, \rho\rho, D^*\pi, J/\Psi K_{S,L}. \]

Let \( M_1 \) and \( M_2 \) be two final state mesons such that the spectator quark finishes inside \( M_1 \), in naive factorization

\[ \langle M_1 M_2 | \hat{Q}_i | B \rangle \approx F^{B \rightarrow M_1} f_{M_2}. \]

\( F^{B \rightarrow M_1} \) : Form factor for the \( B \rightarrow M_1 \) transition.

\( f_{M_2} \) : Decay constant associated with the \( M_2 \) meson.

Interactions between the spectator quark and \( M_2 \) are ignored.
In QCD factorization

\[
\langle M_1 M_2 | \hat{Q}_i | B \rangle = \sum_j F_{j}^{B \to M_1}(0) \int_0^1 du T_{ij}^I(u) \Phi_{M_2}(u) + (M_1 \leftrightarrow M_2)
\]

\[
+ \int_0^1 d\xi dudv T_{i}^{II}(\xi, u, v) \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u).
\]

\[\Phi_M:\] Light Cone Distribution Amplitude (LCDA) for the meson \(M\).

\[T_{ij}^I:\] Penguin contributions (calculated perturbatively).

\[T_{i}^{II}:\] Spectator quark interactions (calculated perturbatively).

Power corrections

Important source of uncertainties come from non-factorizable contributions which are $\Lambda_{QCD}/m_b$ suppressed. They arise in:

Hard spectator Scattering

\[
H_i(M_1M_2) \propto \int_0^1 d\xi \frac{\Phi_B(\xi)}{\xi} \int_0^1 dx \int_0^1 dy \left[ \frac{\Phi_{M_2}(x)\Phi_{M_1}(y)}{\bar{x}\bar{y}} + r_{M_1}^{M_2} \frac{\Phi_{M_2}(x)\Phi_{m_1}(y)}{x\bar{y}} \right]
\]

For the first moment of the LCDA of the $B$ meson we have

\[
\int_0^1 d\xi \frac{\Phi_B(\xi)}{\xi} \equiv \frac{m_B}{\lambda_B}
\]

The treatment of these singularities is model dependent. We use

\[
X_H = \left(1 + \rho_H e^{i\phi_H}\right) \ln\frac{m_B}{\Lambda_h}
\]
Power corrections

Annihilation topologies

In analogy with the Hard Spectator Scattering the end point singularities arising from annihilation topologies are parameterized as

$$\chi_A = \left(1 + \rho_A e^{i\phi_A}\right)\ln \frac{m_B}{\Lambda_h}$$

We assign 200% uncertainty to the power suppressed singularities.

$$0 \leq \rho_H \leq 2 \quad 0 \leq \phi_H \leq 2\pi$$

$$0 \leq \rho_A \leq 2 \quad 0 \leq \phi_A \leq 2\pi$$

Our fits are highly affected by the power suppressed divergences arising from annihilation topologies.
Power corrections

To illustrate the size of the uncertainties from power suppressed singularities consider:

\[ B^0 \rightarrow \pi^+ \pi^-, \quad \bar{B}^0 \rightarrow \pi^+ \pi^- \]

The error budget for the observable

\[ S_{\pi \pi} = \frac{2\text{Im} \left( e^{-2i\beta} \frac{\bar{A}_{\pi^+ \pi^-}}{A_{\pi^+ \pi^-}} \right)}{1 + |\frac{\bar{A}_{\pi^+ \pi^-}}{A_{\pi^+ \pi^-}}|^2} \]

is

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta(X_A) )</td>
<td>39.96%</td>
</tr>
<tr>
<td>( \delta(</td>
<td>V_{ub}/V_{cb}</td>
</tr>
<tr>
<td>( \delta(\gamma) )</td>
<td>8.35%</td>
</tr>
<tr>
<td>( \delta(\mu) )</td>
<td>3.33%</td>
</tr>
<tr>
<td>( \delta(m_s) )</td>
<td>3.20%</td>
</tr>
<tr>
<td>( \delta(X_H) )</td>
<td>2.37%</td>
</tr>
<tr>
<td>( \delta(\Lambda_Q^{CD}) )</td>
<td>1.84%</td>
</tr>
<tr>
<td>( \delta(F_{B^{-}}^{\pi}) )</td>
<td>0.86%</td>
</tr>
<tr>
<td>( \sum \delta )</td>
<td>42.27%</td>
</tr>
</tbody>
</table>

Divergences from annihilation topologies play an important role in the final uncertainty!!.
Examples of the regions obtained for the individual observables are

\[ \mathcal{B}(\bar{B} \to X_s \gamma) \]

\[ a_{s/l}^d \]

\[ \alpha \]
Implications on $\Delta \Gamma_d$

$-3.91 < \Delta \Gamma_d;\text{exp}/\Delta \Gamma_d;\text{SM} < 2.60$

$(\Delta \Gamma_d/\Gamma_d)_{\text{exp}}$ from HFAG, online update 2017

$b \rightarrow u\bar{u}d: 0 < \Delta \Gamma_d/\Delta \Gamma_d;\text{SM} < 1.76$

$b \rightarrow c\bar{c}d: -0.93 < \Delta \Gamma_d/\Delta \Gamma_d;\text{SM} < 2.60$
To obtain maximal constraints we assume $\Delta C_{1,2} = \Delta C_{1,2}^{uu} = \Delta C_{1,2}^{cu} = \Delta C_{1,2}^{cc}$.
The CKM angle $\gamma$ can be extracted from

$$r_B e^{i(\delta_B - \gamma)} = \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}$$

New physics effects in $C_1$ and $C_2$ modify $r_B e^{i(\delta_B - \gamma)}$ as

$$r_B e^{i(\delta_B - \gamma)} \to r_B e^{i(\delta_B - \gamma)} \cdot \left[ \frac{C_2 + \Delta C_2 + r_{A'} (C_1 + \Delta C_1)}{C_2 + r_{A'} C_1} \frac{C_2 + r_A C_1}{C_2 + \Delta C_2 + r_A (C_1 + \Delta C_1)} \right] .$$

$$r_{A'} = \frac{\langle \bar{D}^0 K^- | Q^\text{us} \bar{c} | B^- \rangle}{\langle \bar{D}^0 K^- | Q^\text{us} \bar{c} | B^- \rangle} , \quad r_A = \frac{\langle D^0 K^- | Q^\text{us} \bar{c} | B^- \rangle}{\langle D^0 K^- | Q^\text{us} \bar{c} | B^- \rangle} .$$

$$r_B e^{i(\delta_B - \gamma)} \to r_B e^{i(\delta_B - \gamma)} \cdot \left[ 1 + (r_{A'} - r_A) \frac{\Delta C_1}{C_2} \right] .$$

$$\delta \gamma = (r_A - r_{A'}) \frac{\text{Im}\Delta C_1}{C_2}$$
Effects on CKM $\gamma$

Based on a naive estimation of $r_A'$ we obtain the following plot

\[ \gamma = (72.1^{+5.4}_{-5.7})^\circ \]

CKMfitter online update 2018

Preliminary results/ Anomalies and life-times not yet included /Undergoing analysis!
New Physics in tree level non leptonic can be sizeable.

Colour suppressed $\Delta C_1$: $Re \Delta C_1 \approx 0.20$, $Im \Delta C_1 \approx 0.40$

$\Delta \Gamma_d$ can be enhanced by a factor of 2.6 with respect to the SM

$\Delta C_1, \Delta C_2$ affected by: power corrections, renormalization scale, CKM parameters,…

CKM $\gamma$ is sensitive to $Im \Delta C_1$

Reduce the size of $Im \Delta C_1$ using $sin 2\beta$: $A_{B \rightarrow J/\psi K_S}$?

Analysis in progress :)!