NP in hadronic tree-level affects the determination of CKM γ

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Why new Physics at Tree Level?

- Based on the data available there is plenty of room for SM deviations.

- NP effects in semileptonic tree level transitions $b \to c l \nu$:

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

BABAR + LHCb + Belle combination 3.9 σ deviation with respect to the SM.

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

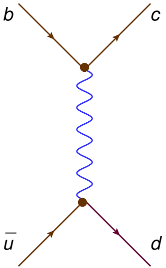
- NP effects in non leptonic b decays to:

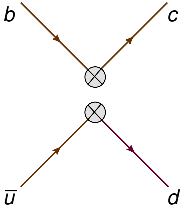
Address the 2010 $D0$ dimuon asymmetry
Bauer and Dunn, Phys. Lett. B 696 (2011) 362, arXiv:106.1629 [hep-ph]

Evaluate enhancements in $\Delta\Gamma_d$
Bobeth, Haisch, Lenz, Pecjak and T-X, JHEP 1406 (2014) 040, arXiv: 1404.2534 [hep-ph]

Determine the impact on the determination of the CKM angle γ
Brod, Lenz, T-X, Wiebusch, Phys. Rev. D.92 (2015) no. 3, 033002, arXiv: 1412.1446 [hep-ph]

Effective field theory formalism

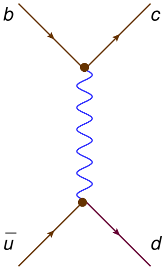


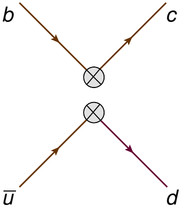


$$\hat{Q}_1 = \left(\bar{c}_\alpha b_\beta\right)_{V-A}\left(\bar{d}_\beta u_\alpha\right)_{V-A} \qquad \hat{Q}_2 = \left(\bar{c}_\alpha b_\alpha\right)_{V-A}\left(\bar{d}_\beta u_\beta\right)_{V-A}.$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\Big(\sum_{p,p'=u,c} \lambda^s_{pp'} \sum_{i=1,2} C_i^{pp'}(\mu)\hat{Q}_i^{pp'}$$

Effective field theory formalism





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

$$\begin{aligned}\mathcal{H}_{eff} &= \frac{G_F}{\sqrt{2}}\Bigg(\sum_{p,p'=u,c}\lambda^s_{pp'}\sum_{i=1,2}C_i^{pp'}(\mu)\hat{Q}_i^{pp'} \\ &\quad + \sum_{p=u,c}\lambda^s_p\sum_{i=3}^{10}C_i(\mu)\hat{Q}_i + C_{7\gamma}\hat{Q}_{7\gamma} + C_{8g}\hat{Q}_{8g}\Bigg) + h.c.,\end{aligned}$$

$$\lambda^s_p = V_{pb}V^*_{ps} \qquad \lambda^s_{pp'} = V_{pb}V^*_{p's}$$

New Physics effects

$$C_{1,2}^{SM} \to C_{1,2}^{SM} + \Delta C_{1,2}.$$

New Physics effects are propagated to the other coefficients through the R.G.E

$$\mu \frac{d\vec{C}}{d\mu} = \hat{\gamma}^T \vec{C}. \qquad \vec{C}(\mu) = \hat{\boldsymbol{U}}(\mu, \mu_W, \alpha)\vec{C}(M_W)$$

We consider NLO expressions initial conditions for the Wilson coefficients (strong + electroweak)

$$\begin{aligned}\vec{C}(M_W) &= \vec{C}_s^{(0)}(M_W) + \frac{\alpha_s(M_W)}{4\pi}\vec{C}_s^{(1)}(M_W) \\ &+ \frac{\alpha}{4\pi}\left[\vec{C}_e^{(0)}(M_W) + \frac{\alpha_s(M_W)}{4\pi}\vec{C}_e^{(1)}(M_W) + \vec{R}_e^{(0)}(M_W)\right].\end{aligned}$$

Beneke, Buchalla, Neubert and Sachrajda, Nucl. Phys. B 606 (2001) 245-321, arXiv:0104110 [hep-ph]

χ^2 Fit

To assess the size of $\Delta C_{1,2}$ we perform a χ-squared fit using MyFitter

M. Wiebusch, Comput. Phys. Commun. 184 (2013) 2438.

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

$$\vec{\omega} = (\vec{\lambda}, \Delta C_1(M_W), \Delta C_2(M_W))$$

$\vec{\lambda}$: CKM parameters, μ, f_π,...$\Rightarrow$ nuisance parameters.

QCD Factorization

Different observables associated with the decays:

$B \to \pi\pi, \rho\pi, \rho\rho, D^*\pi, J/\Psi K_{S,L}$

Introduce the amplitudes obtained using QCD factorization

$$
\begin{aligned}
\langle M_1 M_2 | \hat{Q}_i | B \rangle &= \sum_j F_j^{B\to M_1}(0) \int_0^1 du T_{ij}^I(u) \Phi_{M_2}(u) + (M_1 \leftrightarrow M_2) \\
&+ \int_0^1 d\xi du dv T_i^{II}(\xi, u, v) \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u).
\end{aligned}
$$

Φ_M : Light Cone Distribution Amplitude (LCDA) for the meson M.

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

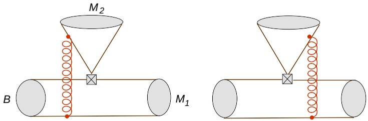
T_i^{II} : Spectator quark interactions (calculated perturbatively).

Beneke, Buchalla, Neubert and Sachrajda, Nucl. Phys. B 591 (2000) 313, arXiv:0006124 [hep-ph]

Power corrections

Important source of uncertainties from non-factorizable contributions:

Hard spectator Scattering



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

$\Phi_{m_1}(y)$ Twist-3 LCDA $\Rightarrow$ Singular under integration

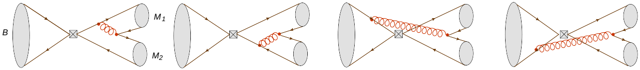
$$\int_0^1 \frac{dy}{\bar{y}} \Phi_{m_1}(y) \quad = \quad \Phi_{m_1}(1) X_H^{M_1} + \int_0^1 \frac{dy}{[\bar{y}]_+} \Phi_{m_1}(y)$$

$$\int_0^1 d\xi \frac{\Phi_B(\xi)}{\xi} \equiv \frac{m_B}{\lambda_B} \qquad X_H = \left(1 + \rho_H e^{i\phi_H}\right) \ln \frac{m_B}{\Lambda_h}$$

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

Power corrections

Annihilation topologies



End point singularities to be treated in analogy with Hard Spectator Scattering

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

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

Our fits are highly affected by the ranges for the power correction parameters (mostly annihilation topologies).

Power corrections

Consider the processes:

$$B^0 \to \pi^+\pi^-, \qquad \bar{B}^0 \to \pi^+\pi^-$$

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

Parameter	Relative Error
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	10.22%
$\delta(\gamma)$	7.25%
$\delta(\mu)$	3.87%
$\delta(F_+^{B\to\pi})$	1.97%
$\delta(\lambda_B)_\pm$	1.55%
$\delta(m_s)$	1.45%
$\delta(\Lambda_5^{QCD})$	1.10%
$\left(\sum\delta\right)_1$	13.50%
$\delta(X_A)^{max}$	44.93%
$\delta(X_H)^{max}$	2.67%
$\sum\delta$	46.98%

Annihilation topologies account for most of the uncertainty.

Decay Transitions

$b \to u\bar{u}d$

- $B \to \pi\pi$:

$$R_{\pi\pi} = \frac{\Gamma(B^- \to \pi^0\pi^-)}{d\Gamma(\bar{B}_d^0 \to \pi^+ l^- \bar{\nu}_l)/dq^2|_{q^2=0}} \qquad S_{\pi\pi} = \frac{2Im\left(e^{-2i\beta}\frac{\bar{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}\right)}{1+|\frac{\bar{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}|^2}$$

- $B \to \rho\pi$

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

- $B \to \rho\rho$

$$R_{\rho\rho} = \mathcal{B}_r(B^- \to \rho_L^- \rho_L^0)/\mathcal{B}_r(\bar{B}_d^0 \to \rho_L^+ \rho_L^-)$$

Decay Transitions

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

- $B \to D^{*}\pi$

$$R_{D^*\pi} = \frac{\Gamma(\bar{B}^0 \to D^{*+}\pi^-)}{d\Gamma(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)/dq^2|_{q^2=m_\pi^2}} \qquad S_{\rho\pi} = \frac{2Im\left(e^{-2i\beta}\frac{\bar{A}_{D^{*0}\pi^0}}{A_{D^{*0}\pi^0}}\right)}{1+|\frac{\bar{A}_{D^{*0}\pi^0}}{A_{D^{*0}\pi^0}}|^2}$$

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

- $B \to X_d\gamma$

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

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

- $B \to X_s\gamma$

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

- $B \to J/\Psi K$

$$S_{\rho\pi} = \frac{2Im\left(e^{-2i\beta}\frac{\bar{A}_{J/\Psi K}}{A_{J/\Psi K}}\right)}{1+|\frac{\bar{A}_{J/\Psi K}}{A_{J/\Psi K}}|^2}$$

Multiple channel constraints

$$i\frac{d}{dt}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \hat{\mathcal{H}}\begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix}$$

$$\begin{aligned} \Delta M &= M_H - M_L, \\ \Delta\Gamma &= \Gamma_L - \Gamma_H. \end{aligned}$$

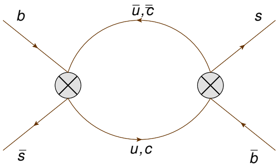
$$\hat{\mathcal{H}} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{11} - \frac{i}{2}\Gamma_{11} \end{pmatrix},$$

$$i\frac{d}{dt}\begin{pmatrix} |B_H(t)\rangle \\ |B_L(t)\rangle \end{pmatrix} = \begin{pmatrix} \lambda_H & 0 \\ 0 & \lambda_L \end{pmatrix}\begin{pmatrix} |B_H(t)\rangle \\ |B_L(t)\rangle \end{pmatrix}.$$

$$\begin{aligned} \lambda_H &= M_H - \frac{i}{2}\Gamma_H, \\ \lambda_L &= M_L - \frac{i}{2}\Gamma_L, \end{aligned}$$

$$\begin{aligned} \Delta M &= M_H - M_L, \\ \Delta\Gamma &= \Gamma_L - \Gamma_H. \end{aligned}$$

Multiple channel constraints

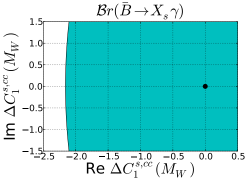


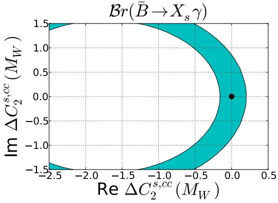
- $a_s^{sl} = |\Gamma_{12}|/|M_{12}| \sin\phi_{12}$: $b \to u\bar{u}s$, $b \to u\bar{c}s$, $b \to c\bar{c}s$
- $\Delta\Gamma_s$: $b \to u\bar{u}s$, $b \to u\bar{c}s$, $b \to c\bar{c}s$
- a_d^{sl}: $b \to u\bar{u}d$, $b \to u\bar{c}d$, $b \to c\bar{c}d$

Individual Fit Examples

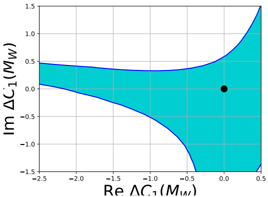
Probe for New weak phases by allowing ΔC_1 and ΔC_2 to be complex

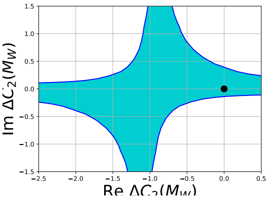
$\mathcal{B}(\bar{B} \to X_s \gamma)$





a_{sl}^d

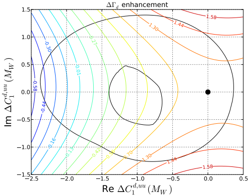


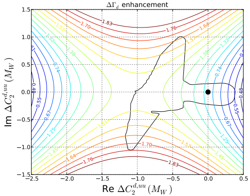


$$-3.91 < \Delta\Gamma_{d;exp}/\Delta\Gamma_{d;SM} < 2.60$$

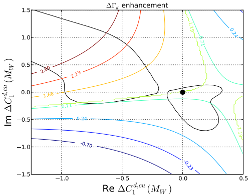
$(\Delta\Gamma_d/\Gamma_d)_{exp}$ *from HFAG, online update 2017*

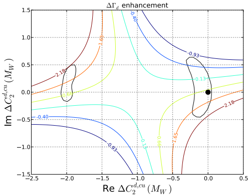
$b \to u\bar{u}d$: $0 < \Delta\Gamma_d/\Delta\Gamma_{d;SM} < 1.76$





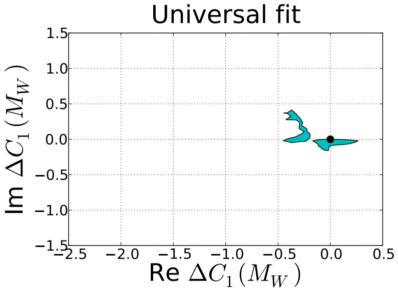
$b \to c\bar{u}d$: $-0.93 < \Delta\Gamma_d/\Delta\Gamma_{d;SM} < 2.60$

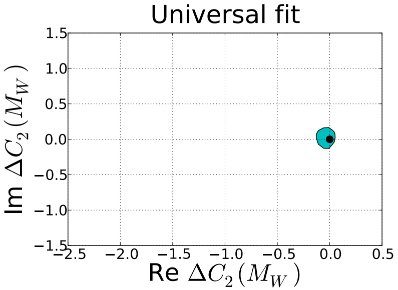




Universal Tree level bounds

Assume $\Delta C_{1,2} = \Delta C^{uu}_{1,2} = \Delta C^{cu}_{1,2} = \Delta C^{cc}_{1,2}$





Effects on CKM γ

The CKM angle γ 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

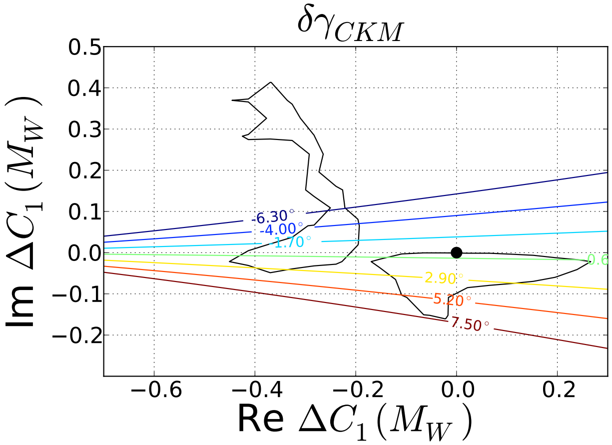
$$r_B e^{i(\delta_B-\gamma)} \to r_B e^{i(\delta_B-\gamma)} \cdot \left[\frac{C_2 + \Delta C_2 + r_{A'}(C_1 + \Delta C_1)}{C_2 + r_{A'} C_1} \frac{C_2 + r_A C_1}{C_2 + \Delta C_2 + r_A(C_1 + \Delta C_1)} \right] .$$

$$r_{A'} = \frac{\langle \bar{D}^0 K^- | Q_1^{\bar{u}cs} | B^- \rangle}{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle} , \quad r_A = \frac{\langle D^0 K^- | Q_1^{\bar{c}us} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle} .$$

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

$$\delta\gamma = (r_A - r'_A) \frac{Im \Delta C_1}{C_2}$$

Effects on CKM γ



$\gamma = 72.1^\circ \pm \delta\gamma \qquad -5.8^\circ < \delta\gamma < 5.4^\circ$

CKMfitter online update 2018

Use CKM γ to bound ΔC_1

Conclusions and outlook

- New Physics in tree level non leptonic can be sizeable.
- Colour suppressed ΔC_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 γ is sensitive to *Im* ΔC_1
- Reduce the size of *Im* ΔC_1 using $\sin 2\beta$: $A_{B\to J/\Psi K_S}$?