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

Gilberto Tetlalmatzi-Xolocotzi

Nikhef Theory Division

In collaboration with: Alexander Lenz

March 31, 2019

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 $b \to cl\nu$:

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

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 semileptonic tree level transitions $b \to ul\nu$:

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

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

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

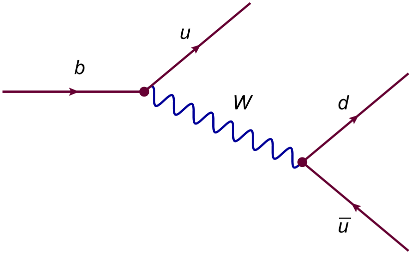
Banelli, Fleischer, Jaarsma and T-X, Eur.Phys.J. C78 (2018) no.11, 911
arXiv:1809.09051 [hep-ph]

New Physics at tree level in non-leptonic B decays

We want to explore the possibility of having NP in the non leptonic processes:

$$b \to u\bar{u}d \qquad b \to u\bar{c}d \qquad b \to c\bar{u}d \qquad b \to c\bar{c}d \qquad (d \to s).$$

In the SM these processes proceed at tree level



New Physics at tree level in non-leptonic B decays

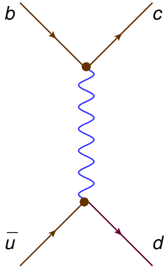
The possibility of having NP at tree level in hadronic B decays has been considered before to:

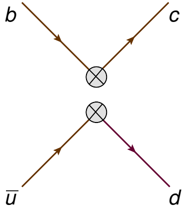
- Address the 2010 $D0$ dimuon asymmetry
  Bauer and Dunn, Phys. Lett. B 696 (2011) 362, arXiv:106.1629 [hep-ph]
- Evaluate enhancements in the B_d^0 observable $\Delta\Gamma_d$
  Bobeth, Haisch, Lenz, Pecjak and T-X, JHEP 1406 (2014) 040, arXiv: arXiv:1404.2531 [hep-ph]
- Investigate the $\Delta\mathcal{A}_{CP}$ puzzle in $B \to K\pi$ decays
  Bobeth, Gorbahn, Vickers, Eur.Phys.J. C75 (2015) no.7, 340, arXiv:1409.3252 [hep-ph]
- Evaluate 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]

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





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

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

The tree level effective Hamiltonian is

$$\mathcal{H}_{eff}^{Tree} = \frac{G_F}{\sqrt{2}} \sum_{p,p'=u,c} \lambda^d_{pp'} \left(C_i^{pp'}(\mu)\hat{Q}_1^{pp'} + C_i^{pp'}(\mu)\hat{Q}_2^{pp'} \right) \qquad \lambda^d_{pp'} = V_{pb}V^*_{p'd}$$

In the SM at NLO

$$C_1(m_b) \sim -0.19 \qquad C_2(m_b) \sim 1.08$$

Effective field theory formalism

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

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

Effective field theory formalism

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

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

Effective field theory formalism

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

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

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

$\hat{Q}_1^{pp'} - \hat{Q}_2^{pp'}$: Tree level.

$\hat{Q}_3 - \hat{Q}_6$: QCD Penguins. $\hat{Q}_7 - \hat{Q}_{10}$: Electro-weak Penguins.

$\hat{Q}_{7\gamma}$: Electromagnetic operator. $\hat{Q}_{7g}$: Chromomagnetic operator.

Introducing NP effects at tree level

The NP effects are introduced at the matching scale M_W

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

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

To implement the fit we use the software MyFitter

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

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

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

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

$$\vec{\lambda}_{nuisance} = |V_{ub}/V_{cb}|, |V_{us}|, \mu, f_\pi, F_+^{B\to\pi}, ..., etc$$

Introducing NP effects at tree level

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

$$\mu \frac{d\vec{C}}{d\mu} = \hat{\gamma}^T \vec{C}.$$

the NP effects propagate to the other Wilson coefficients as well

$$\vec{C}(\mu) = \hat{\boldsymbol{U}}(\mu, \mu_W, \hat{\gamma}, \alpha_s, \alpha) \vec{C}(M_W).$$

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

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

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

Introducing NP effects at tree level

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

To obtain bounds on ΔC_1^{NP} and ΔC_2^{NP} we use:

- Branching fractions of hadronic processes.
- CP asymmetries

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

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

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

- Neutral B Mixing observables
- Life-time ratios

The full χ^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

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

- $B \to \pi\pi$:

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

- $B \to \rho\pi$

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

- $B \to \rho\rho$

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

Observables considered

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

- $B \to D^*\pi$

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

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

- $B \to X_d\gamma$

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

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

- $B \to X_s\gamma$

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

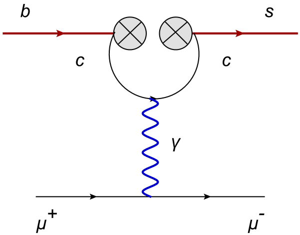
- $B \to J/\Psi K$

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

- Life-time ratio: τ_{B_s}/τ_{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 $\hat{Q}_{9V} = \frac{\alpha}{4\pi}(\bar{\hat{s}}_L \gamma_\mu \hat{b}_L)(\bar{\hat{\ell}}\gamma^\mu \hat{\ell})$



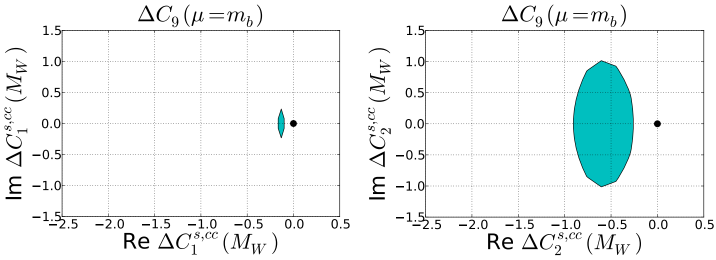
$$\Delta C_9^{\text{eff}}\Big|_{\mu=m_b} = \Big[8.48\ \Delta C_1 + 1.96\ \Delta C_2\Big]\Big|_{\mu=M_W}.$$

Jager, Kirk, Lenz and Leslie, Phys.Rev. D97 (2018) no.1, 015021, arXiv:1701.09183 [hep-ph]

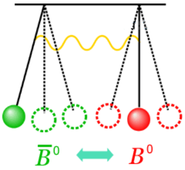
Using the results for complex $\Delta C_9^{\mathrm{eff}}$ provided in

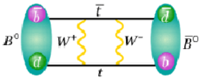
Kumar-Alok, Bhattacharya, Kumar, Kumar, London, and Sankar, Phys. Rev. D 96, 015034 (2017), arXiv:1703.09247 [hep-ph]

we obtain the following regions



Constraints from neutral B meson mixing





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

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

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

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

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

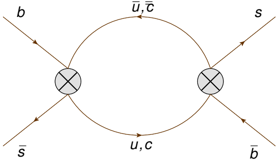
Constraints from neutral B meson mixing

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

Neutral B mixing is described by two observables

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

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



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

QCD Factorization

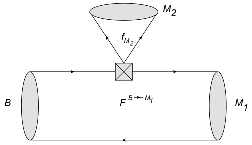
We include different observables calculated through the QCD Factorization formalism:

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

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

$$\langle M_1 M_2 | \hat{Q}_i | B \rangle \quad \approx \quad F^{B\to M_1} f_{M_2}.$$

$F^{B\to M_1}$	:	Form factor for the $B \to M_1$ transition.
f_{M_2}	:	Decay constant associated with the M_2 meson.



Interactions between the spectator quark and M_2 are ignored.

QCD Factorization

In QCD factorization

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

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

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

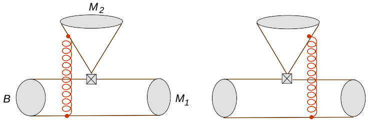
T_i^{II} : Spectator quark interactions (calculated perturbatively).

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

Power corrections

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

Hard spectator Scattering



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

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 Twist-3 LCDA $\Phi_{m_1}(y)$ is singular under integration

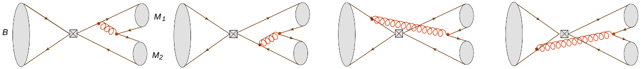
$$\int_0^1 \frac{dy}{\bar{y}} \Phi_{m_1}(y) = \Phi_{m_1}(1) X_H^{M_1} + \int_0^1 \frac{dy}{[\bar{y}]_+} \Phi_{m_1}(y)$$

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

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

We assign 200% uncertainty to the power suppressed singularities.

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

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

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:

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

The error budget for the observable $S_{\pi\pi} = \frac{2Im\left(e^{-2i\beta}\frac{\bar{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}\right)}{1+|\frac{\bar{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}|^2}$ is

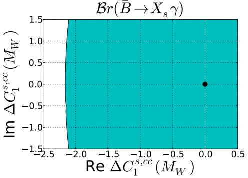
Parameter	Relative Error
$\delta(X_A)$	39.96%
$\delta(\lvert V_{ub}/V_{cb}\rvert)$	9.45%
$\delta(\gamma)$	8.35%
$\delta(\mu)$	3.33%
$\delta(m_s)$	3.20%
$\delta(X_H)$	2.37%
$\delta(\Lambda_5^{QCD})$	1.84%
$\delta(F_+^{B\to\pi})$	0.86%
$\sum\delta$	42.27%

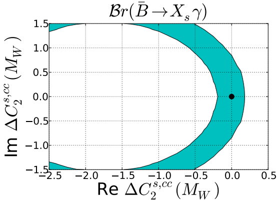
Divergences from annihilation topologies play an important role in the final uncertainty!!.

Individual Fit Examples

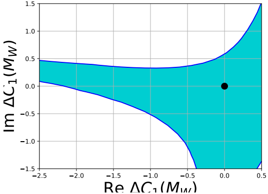
Examples of the regions obtained for the individual observables are

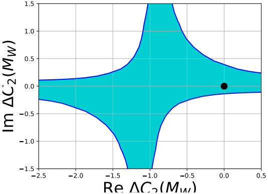
$\mathcal{B}(\bar{B} \to X_s\gamma)$





a_{sl}^d



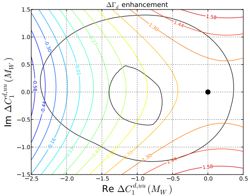


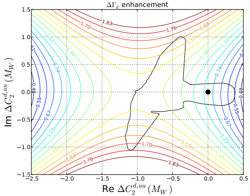
Implications on $\Delta\Gamma_d$

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

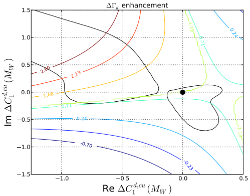
$(\Delta\Gamma_d/\Gamma_d)_{exp}$ *from HFAG, online update 2017*

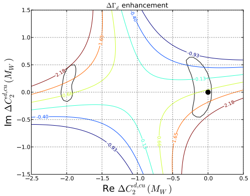
$b \to u\bar{u}d$: $0 < \Delta\Gamma_d/\Delta\Gamma_{d;SM} < 1.76$





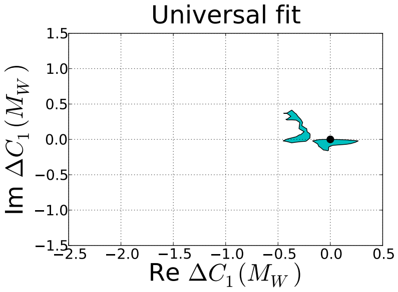
$b \to c\bar{u}d$: $-0.93 < \Delta\Gamma_d/\Delta\Gamma_{d;SM} < 2.60$

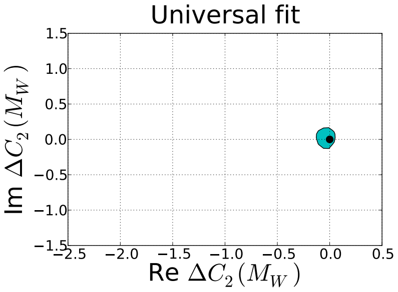




Universal Tree level bounds

To obtain maximal constraints we 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

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

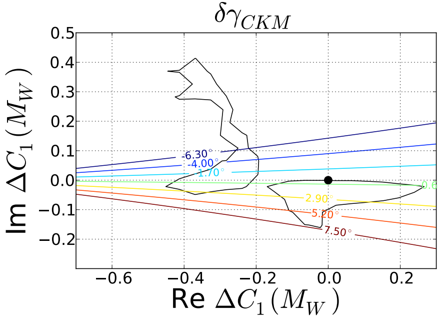
$$r_{A'} = \frac{\langle \bar{D}^0 K^- | Q_1^{\bar{u}cs} | B^- \rangle}{\langle \bar{D}^0 K^- | Q_2^{\bar{u}cs} | B^- \rangle} , \quad r_A = \frac{\langle D^0 K^- | Q_1^{\bar{c}us} | B^- \rangle}{\langle D^0 K^- | Q_2^{\bar{c}us} | B^- \rangle} .$$

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

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

Effects on CKM γ

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!

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 $\sin 2\beta$: $A_{B\to J/\Psi K_S}$?
- Analysis in progress :)!