

New physics in $b \rightarrow sll$ decays with complex Wilson coefficients.

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Anomalies 2021

Based on [Nucl.Phys.B 969 \(2021\) 1154797](#)

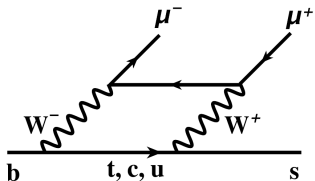
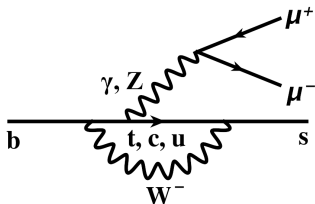
In collaboration with Soumitra Nandi, Sunando Patra and Aritra Biswas.



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Anomalies in flavor physics

- Flavor changing neutral currents (FCNCs), potential probe of physics at higher energy scales \rightarrow loop-suppressed amplitudes within the Standard Model (SM).
- Deviations in few angular observables ($P'_5 \sim 3\sigma$) and theoretically clean ratios (R_K and R_{K^*}) from their respective SM predictions.



$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} \left(\lambda_t \mathcal{H}_{eff}^{(t)} + \lambda_u \mathcal{H}_{eff}^{(u)} \right) \quad (1)$$

$$\mathcal{H}_{eff}^{(t)} = C_1 \mathcal{O}_1^c + C_2 \mathcal{O}_2^c + \sum_{i=3}^6 C_i \mathcal{O}_i + \sum_{i=7,8,9,10,P,S} (C_i \mathcal{O}_i + C'_i \mathcal{O}'_i)$$

$$\mathcal{H}_{eff}^{(u)} = C_1 (\mathcal{O}_1^c - \mathcal{O}_1^u) + C_2 (\mathcal{O}_2^c - \mathcal{O}_2^u).$$

$$\mathcal{O}_1 = (\bar{s}_\alpha q_\beta)_{V-A} (\bar{q}_\beta b_\alpha)_{V-A},$$

$$\mathcal{O}_2 = (\bar{s}q)_{V-A} (\bar{q}b)_{V-A},$$

$$\mathcal{O}_3 = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V-A},$$

$$\mathcal{O}_4 = (\bar{s}_\alpha b_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V-A},$$

$$\mathcal{O}_5 = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V+A},$$

$$\mathcal{O}_6 = (\bar{s}_\alpha b_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A},$$

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu},$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s} \sigma_{\mu\nu} T^a P_R b) G^{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_L b) (\bar{l} \gamma^\mu l),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_L b) (\bar{l} \gamma^\mu \gamma_5 l),$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b) (\bar{l} l),$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b) (\bar{l} \gamma_5 l),$$

$$\mathcal{O}'_7 = \frac{e}{g^2} m_b (\bar{s} \sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

$$\mathcal{O}'_8 = \frac{1}{g} m_b (\bar{s} \sigma_{\mu\nu} T^a P_L b) G^{\mu\nu},$$

$$\mathcal{O}'_9 = \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_R b) (\bar{l} \gamma^\mu l),$$

$$\mathcal{O}'_{10} = \frac{e^2}{g^2} (\bar{s} \gamma_\mu P_R b) (\bar{l} \gamma^\mu \gamma_5 l),$$

$$\mathcal{O}'_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b) (\bar{l} l),$$

$$\mathcal{O}'_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b) (\bar{l} \gamma_5 l) \quad (2)$$

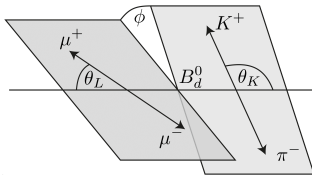
Experimental Inputs

- $B^{(0,+)} \rightarrow K^{(0,+)} \mu^+ \mu^-$: Differential branching fractions and isospin asymmetries (LHCb and Belle), binned data on the angular observables (A_{FB} and F_H) for $B^+ \rightarrow K^+ \mu^+ \mu^-$ (CMS) and inputs on R_K (LHCb and Belle).
- $B \rightarrow K^* \mu^+ \mu^-$: Differential branching fractions and isospin asymmetries (LHCb), angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays (LHCb and ATLAS), P'_4 and P'_5 for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ (Belle) and R_{K^*} (LHCb and Belle).
- $B_s \rightarrow \phi \mu^+ \mu^-$: Differential branching fractions and angular observables (LHCb).
- $B_s \rightarrow \mu \mu$: Branching fraction (HFLAV).

Decay distribution

- For a vector meson in final state :

$$\begin{aligned}
 \frac{1}{d(\Gamma + \bar{\Gamma})} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = & \frac{9}{32\pi} \left[\frac{3}{4}(1 - F_L)\sin^2\theta_K \right. \\
 & + F_L\cos^2\theta_K \\
 & + \frac{1}{4}(1 - F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l \\
 & + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi \\
 & + S_5\sin 2\theta_K\sin\theta_l\cos\phi \\
 & + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi \\
 & \left. + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi \right]
 \end{aligned}
 \tag{3}$$



- $P_1 = \frac{2S_3}{1-F_L}, \quad P_2 = \frac{2}{3} \frac{A_{FB}}{(1-F_L)}, \quad P_3 = \frac{-S_9}{1-F_L}, \quad P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$

- Normalized angular distribution for pseudoscalar meson :

$$\frac{1}{\Gamma_l} \frac{d\Gamma_l}{d\cos\theta} = \frac{3}{4}(1 - F_H^l)(1 - \cos^2\theta) + \frac{1}{2}F_H^l + A_{FB}^l\cos\theta
 \tag{4}$$

- Complex new physics WCs : $C'_7, \Delta C_9, C'_9, \Delta C_{10}, C'_{10}, C_S, C'_S, C_P$ and C'_P .
- 3 datasets: **Moment(LHCb 2016)**, **Likelihood(LHCb 2016)**, **Likelihood(LHCb 2020)** - **No asymmetric observables**.
- Statistical analysis optimizing a χ^2 statistic.

$$\chi^2(C^{NP}) = [O_{exp} - O_{th}(C^{NP})]^T [C_{exp} + C_{th}]^{-1} [O_{exp} - O_{th}(C^{NP})]$$

- In the post-process for each fit, obtain fit-quality using p-value and find outliers.
- Model selection out of all possible combinations of the WCs(1022 combinations - Real + Real and Imaginary) - **Akaike's Information Criterion (AICc)** and **cross-validation**.

One operator scenarios

Dataset	χ^2/DOF	p-val(%)	C_7		χ^2/DOF	p-val(%)	ΔC_9	
			Value	Value			Value	Value
Likelihood 2020	279.5/210	9.4×10^{-2}	$Re(C_7) \rightarrow -0.039 \pm 0.013$	$Im(C_7) \rightarrow -0.026 \pm 0.101$	202.89/210	62.5	$Re(\Delta C_9) \rightarrow -1.10 \pm 0.11$	$Im(\Delta C_9) \rightarrow 1.27 \pm 0.37$
Likelihood 2016	306.45/249	0.7	$Re(C_7) \rightarrow -0.03 \pm 0.01$	$Im(C_7) \rightarrow -0.002 \pm 0.025$	235.79/249	71.6	$Re(\Delta C_9) \rightarrow -1.21 \pm 0.14$	$Im(\Delta C_9) \rightarrow -1.25 \pm 0.44$
Moments 2016	291.85/271	18.4	$Re(C_7) \rightarrow -0.031 \pm 0.016$	$Im(C_7) \rightarrow -0.0057 \pm 0.0300$	241.7/271	89.9	$Re(\Delta C_9) \rightarrow -1.24 \pm 0.18$	$Im(\Delta C_9) \rightarrow 1.19 \pm 0.48$
			C_9				ΔC_{10}	
Likelihood 2020	287.9/210	2.9×10^{-2}	$Re(C_9) \rightarrow -0.077 \pm 0.149$	$Im(C_9) \rightarrow -0.70 \pm 0.54$	276.17/210	0.15	$Re(\Delta C_{10}) \rightarrow 0.64 \pm 0.18$	$Im(\Delta C_{10}) \rightarrow 1.79 \pm 0.29$
Likelihood 2016	310.72/249	0.47	$Re(C_9) \rightarrow -0.13 \pm 0.15$	$Im(C_9) \rightarrow -0.15 \pm 0.71$	303.22/249	1.1	$Re(\Delta C_{10}) \rightarrow 0.39 \pm 0.15$	$Im(\Delta C_{10}) \rightarrow 0.45 \pm 0.50$
Moments 2016	295.4/271	14.8	$Re(C_9) \rightarrow -0.060 \pm 0.148$	$Im(C_9) \rightarrow -0.084 \pm 0.423$	281.7/271	31.5	$Re(\Delta C_{10}) \rightarrow 0.51 \pm 0.14$	$Im(\Delta C_{10}) \rightarrow -0.11 \pm 0.68$
			C_{10}				C_S	
Likelihood 2020	278.1/210	0.1	$Re(C_{10}) \rightarrow 0.33 \pm 0.11$	$Im(C_{10}) \rightarrow -0.21 \pm 0.81$	288.55/210	2.6×10^{-2}	$Re(C_S) \rightarrow -0.029 \pm 0.483$	$Im(C_S) \rightarrow -0.032 \pm 0.440$
Likelihood 2016	303.0/249	1.1	$Re(C_{10}) \rightarrow 0.33 \pm 0.11$	$Im(C_{10}) \rightarrow 0.02 \pm 0.28$	311.19/249	0.4	$Re(C_S) \rightarrow -0.04 \pm 0.04$	$Im(C_S) \rightarrow 0.0017 \pm 0.3043$
Moments 2016	290.2/271	20.2	$Re(C_{10}) \rightarrow 0.28 \pm 0.12$	$Im(C_{10}) \rightarrow -0.0030 \pm 0.3175$	295.4/271	14.8	$Re(C_S) \rightarrow -0.027 \pm 0.279$	$Im(C_S) \rightarrow 0.030 \pm 0.251$
			C_P				C_S	
Likelihood 2020	288.52/210	2.6×10^{-2}	$Re(C_P) \rightarrow -0.0075 \pm 0.0135$	$Im(C_P) \rightarrow 0.003 \pm 0.241$	288.51/210	2.6×10^{-2}	$Re(C_S) \rightarrow -0.044 \pm 0.053$	$Im(C_S) \rightarrow 0.0055 \pm 0.3001$
Likelihood 2016	311.22/249	0.4	$Re(C_P) \rightarrow -0.0047 \pm 0.1564$	$Im(C_P) \rightarrow 0.02 \pm 0.85$	311.22/249	0.4	$Re(C_S) \rightarrow -0.04 \pm 0.17$	$Im(C_S) \rightarrow -0.01 \pm 0.62$
Moments 2016	295.2/271	15	$Re(C_P) \rightarrow 0.26 \pm 0.12$	$Im(C_P) \rightarrow -0.019 \pm 0.847$	295.4/271	14.8	$Re(C_S) \rightarrow -0.035 \pm 0.157$	$Im(C_S) \rightarrow -0.020 \pm 0.263$
			C_P					
Likelihood 2020	288.49/210	2.6×10^{-2}	$Re(C_P) \rightarrow 0.0078 \pm 0.0125$	$Im(C_P) \rightarrow -0.002 \pm 0.182$				
Likelihood 2016	311.2/249	0.4	$Re(C_P) \rightarrow 0.007 \pm 0.013$	$Im(C_P) \rightarrow -0.0027 \pm 0.2648$				
Moments 2016	295.4/271	14.8	$Re(C_P) \rightarrow 0.0061 \pm 0.0135$	$Im(C_P) \rightarrow 0.0021 \pm 0.3384$				

Results (Likelihood 2020 dataset)

- With CP-asymmetric observables in $B_s \rightarrow \phi\mu\mu$ -

χ_{Min}^2/DOF	p -value (%)	Scenario
206.517/211	57.4	$Re(\Delta C_9) \rightarrow -1.05 \pm 0.11$
202.889/210	62.5	$Re(\Delta C_9) \rightarrow -1.10 \pm 0.11$ $Im(\Delta C_9) \rightarrow 1.27^{+0.33}_{-0.43}$

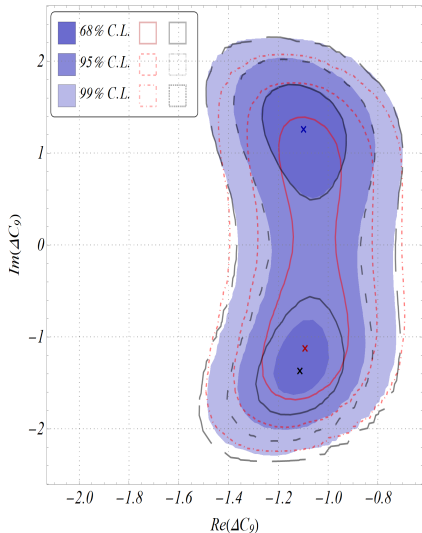
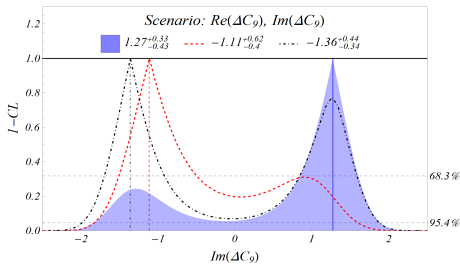
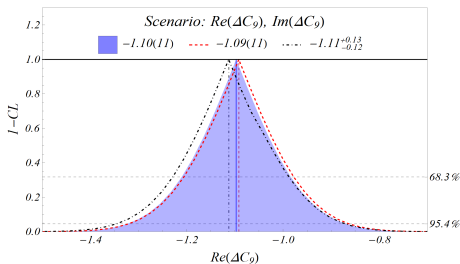
- Without CP-asymmetric observables in $B_s \rightarrow \phi\mu\mu$ -

χ_{Min}^2/DOF	p -value (%)	Scenario
198.226/199	50.2	$Re(\Delta C_9) \rightarrow -1.05 \pm 0.11$
194.926/198	54.8	$Re(\Delta C_9) \rightarrow -1.11 \pm 0.12$ $Im(\Delta C_9) \rightarrow -1.36^{+0.44}_{-0.34} \cup [0.84, 1.59]$

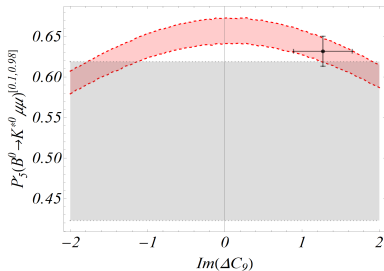
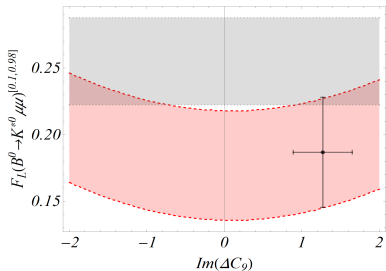
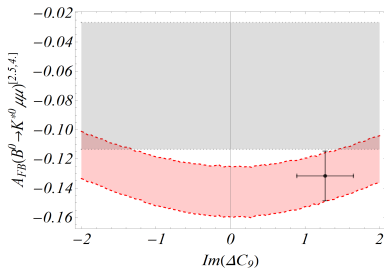
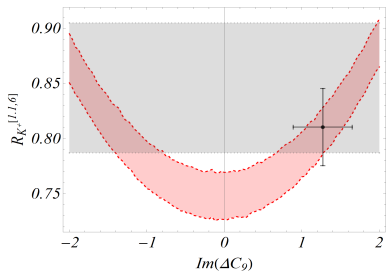
- With CP-asymmetric observables in $B \rightarrow K^*\mu\mu$ (From Likelihood 2016 dataset) -

χ_{Min}^2/DOF	p -value (%)	Scenario
239.768/246	60	$Re(\Delta C_9) \rightarrow -1.06 \pm 0.11$
238.105/245	61.2	$Re(\Delta C_9) \rightarrow -1.09 \pm 0.11$ $Im(\Delta C_9) \rightarrow -1.11^{+0.62}_{-0.4}$

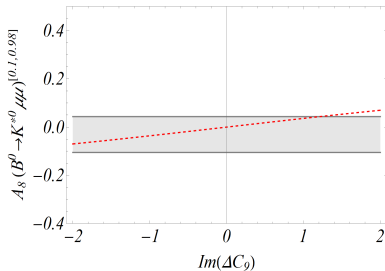
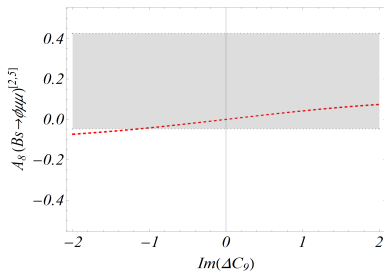
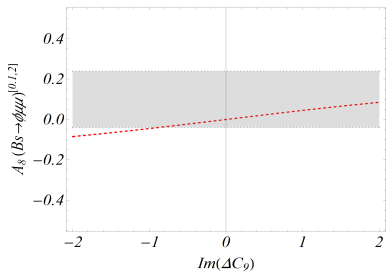
Parameter spaces



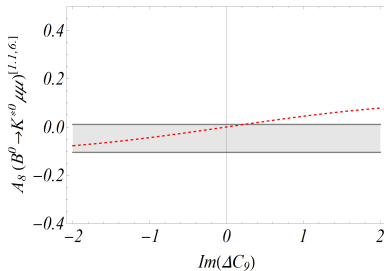
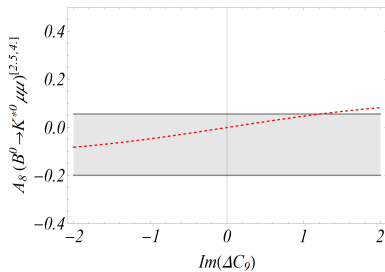
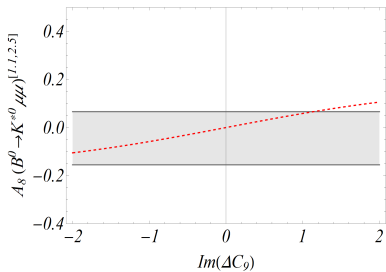
Observables sensitive to $Im(\Delta C_9)$



Observables responsible for sign change in $Im(\Delta C_9)$



Observables responsible for sign change in $Im(\Delta C_9)$



- Akaike's Information Criteria -

$$AIC_c = \chi_{min}^2 + 2K + \frac{2K(K+1)}{n-K-1},$$

n = sample size and K = no. of parameters

- Selected models : $\Delta AIC_c^i = AIC_c^i - AIC_c^{min}$

- **Akaike's Information Criteria -**

$$AIC_c = \chi_{min}^2 + 2K + \frac{2K(K+1)}{n-K-1},$$

n = sample size and K = no. of parameters

- **Selected models : $\Delta AIC_c^i = AIC_c^i - AIC_c^{min}$**

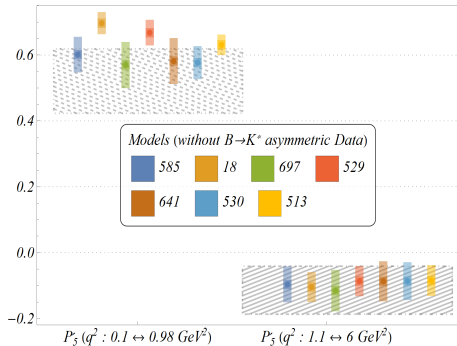
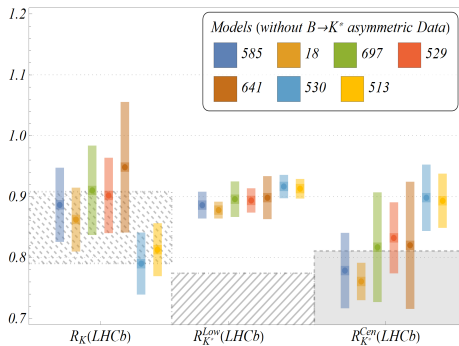
- **Cross-Validation (LOOCV) -**

One of the data points left out and the rest of the sample (“training set”) is optimized for a particular model. Use the result to find the predicted residual ($\frac{\mathcal{O}_i^{exp} - \mathcal{O}_i(C^k)}{\Delta \mathcal{O}_i}$) for the left out data point. Repeat for all data points and calculate MSE for the model.

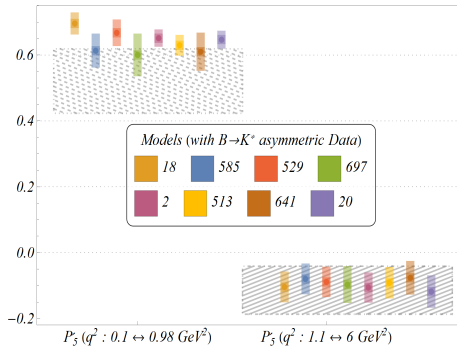
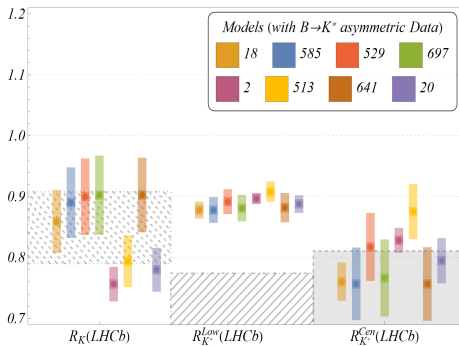
Selected models

Model	ΔAIC_c	$MSE_{X.Val}$	χ^2_{Min}/dof	p-value (%)	Parameters
585.	0.	0.989	189.05/206	79.6	$Re(\Delta C_9) \rightarrow -1.36 \pm 0.24$, $Im(\Delta C_9) \rightarrow 2.05 \pm 0.36$, $Re(C'_9) \rightarrow 0.57 \pm 0.23$, $Im(C'_9) \rightarrow 0.14 \pm 0.25$, $Re(\Delta C_{10}) \rightarrow 0.51 \pm 0.22$, $Im(\Delta C_{10}) \rightarrow -0.53 \pm 0.46$
18.	2.01	0.942	199.41/210	68.9	$Re(\Delta C_9) \rightarrow -1.08 \pm 0.10$, $Re(C'_9) \rightarrow 0.5 \pm 0.18$
697.	3.5	0.97	188.25/204	77.9	$Re(\Delta C_9) \rightarrow -1.4 \pm 0.24$, $Im(\Delta C_9) \rightarrow 1.93 \pm 0.49$, $Re(C'_9) \rightarrow 0.56 \pm 0.23$, $Im(C'_9) \rightarrow 0.31 \pm 0.5$, $Re(\Delta C_{10}) \rightarrow 0.52 \pm 0.22$, $Im(\Delta C_{10}) \rightarrow -0.51 \pm 0.41$ $Re(C'_{10}) \rightarrow -0.032 \pm 0.18$, $Im(C'_{10}) \rightarrow 0.75 \pm 0.82$
529.	3.8	0.977	197.05/208	69.6	$Re(\Delta C_9) \rightarrow -1.11 \pm 0.11$, $Im(\Delta C_9) \rightarrow -0.12 \pm 0.46$, $Re(C'_9) \rightarrow 0.42 \pm 0.23$, $Im(C'_9) \rightarrow -1.21 \pm 0.41$
641.	4.94	1.01	189.69/204	75.6	$Re(C'_7) \rightarrow 0 \pm 0.0136$, $Im(C'_7) \rightarrow 0 \pm 0.04$, $Re(\Delta C_9) \rightarrow -1.07 \pm 0.13$, $Im(\Delta C_9) \rightarrow -0.06 \pm 0.3$, $Re(C'_9) \rightarrow 0.61 \pm 0.25$, $Im(C'_9) \rightarrow -1.98 \pm 0.4$, $Re(\Delta C_{10}) \rightarrow 0.6 \pm 0.22$, $Im(\Delta C_{10}) \rightarrow -0.051 \pm 1.25$
530.	5.48	0.99	198.74/208	66.6	$Re(\Delta C_9) \rightarrow -1.34 \pm 0.26$, $Im(\Delta C_9) \rightarrow 1.95 \pm 0.44$, $Re(\Delta C_{10}) \rightarrow 0.32 \pm 0.23$, $Im(\Delta C_{10}) \rightarrow -0.56 \pm 0.57$
513.	5.49	0.98	202.89/210	62.5	$Re(\Delta C_9) \rightarrow -1.1 \pm 0.11$, $Im(\Delta C_9) \rightarrow 1.27 \pm 0.37$

Predictions of R_{K^*} and P'_5



Predictions of R_{K^*} and P_5'



- \mathcal{O}_9 is the only one operator scenario with both real and complex W.Cs that is capable of explaining the present data.
- In all other one operator scenarios, the quality of fits are very poor, with the respective p-values ~ 0 .
- \mathcal{O}_9 with complex WC, though not the best model, is the only one-operator scenario passing all the selection criteria. Some two, three and four-operator scenarios are selected as well, and all of these contain \mathcal{O}_9 (with real or complex WC) as one of the operators.

Thank
you!