Institut de Física
d’Altes Energies

New observables in non-leptonic B decays: Results and discussions

Based on JHEP 06 (2023) 108 and 2404.01186 [hep-ph]. In collaboration with Joaquim Matias, Sebastian Descotes-Genon and Gilberto Tetlalmatzi-Xolocotzi.

Theory vs experiment: Current status

Observable	SM (QCDF)	Experiment	Deviation
$10^6 BR(\bar{B}_d \to K^0\ \bar{K}^0)$	$1.09^{+0.29}_{-0.20}$	1.21 ± 0.16	0.4σ
$10^7 BR(\bar{B}_d \to K^{*0}\ \bar{K}^{*0})_L$	$2.27^{+0.99}_{-0.74}$	$6.04^{+1.81}_{-1.78}$	1.8σ
$10^5 BR(\bar{B}_s \to K^0\ \bar{K}^0)$	$2.80^{+0.89}_{-0.62}$	1.76 ± 0.33	1.6σ
$10^6 BR(\bar{B}_s \to K^{*0}\ \bar{K}^{*0})_{\mathrm{L}}$	$4.36^{+2.23}_{-1.65}$	$2.62^{+0.85}_{-0.75}$	0.9σ
$10^6 BR(\bar{B}_d \to\ \bar{K}^{*0}\phi)_L$	$4.89^{+2.09}_{-1.99}$	$4.96^{+0.31}_{-0.30}$	0.3σ
$10^7 BR(\bar{B}_s \to K^{*0}\ \phi)_L$	$2.19^{+1.05}_{-0.94}$	$5.56^{+2.78}_{-2.27}$	1.3σ
$10^5 (BR(\bar{B}_s \to K^{*0}\ \bar{K}^0)+BR(\bar{B}_s \to K^{*0}\ \bar{K}^0))$	$0.83^{+0.50}_{-0.25}$	$1.98 \pm 0.28 \pm 0.50$	1.4σ
$10^6 BR(\bar{B}_d \to\ \bar{K}^0\phi)$	$4.28^{+2.71}_{-1.50}$	7.3 ± 0.7	1.3σ

Theory vs experiment: Current status

Observable	SM (QCDF)	Experiment	Deviation
$L_{K^*\bar{K}^*}$	$19.53^{+9.14}_{-6.64}$	4.43 ± 0.92	2.6σ
$L_{K\bar{K}}$	$26.00^{+3.88}_{-3.59}$	14.58 ± 3.37	2.4σ
$L_{K^*\phi}$	$22.04^{+7.06}_{-4.88}$	$8.80^{+6.07}_{-2.97}$	1.5σ

$L_{K^*K^*}$: Error Budget

	Relative Error		
Input	$L_{K^*\bar{K}^*}$	$\|P_s\|^2$	$\|P_d\|^2$
f_{K^*}	$(-0.1\%, +0.1\%)$	$(-6.8\%, +7.1\%)$	$(-6.8\%, +7\%)$
$A_0^{B_d}$	$(-22\%, +32\%)$	—	$(-24\%, +28\%)$
$A_0^{B_s}$	$(-28\%, +33\%)$	$(-28\%, +33\%)$	—
λ_{B_d}	$(-0.6\%, +0.2\%)$	$(-4.6\%, +2.1\%)$	$(-4.1\%, +1.9\%)$
$\alpha_2^{K^*}$	$(-0.1\%, +0.1\%)$	$(-3.6\%, +3.7\%)$	$(-3.6\%, +3.6\%)$
X_H	$(-0.2\%, +0.2\%)$	$(-1.8\%, +1.8\%)$	$(-1.6\%, +1.6\%)$
X_A	$(-4.3\%, +4.4\%)$	$(-17\%, +19\%)$	$(-13\%, +14\%)$
κ	$(-1.4\%, +2.2\%)$	—	—
Others	$(-1.3\%, +1.1\%)$	$(-2.7\%, +2.5\%)$	$(-1.6\%, +1.6\%)$

Table 2. Error budget of $L_{K^*\bar{K}^*}$ and $|P_{d,s}|^2$. The relative error of each theoretical input is obtained by varying them individually. The main sources of uncertainty are the form factors, followed by weak annihilation at a significantly smaller level.

Form Factors

$B_{d,s} \to K^*$ form factors [44]	
$A_0^{B_s}(q^2=0)$	$A_0^{B_d}(q^2=0)$
0.314 ± 0.048	0.356 ± 0.046

Relative errors: 16% numerator. 13% denominator

$B_d \to K$ [45] and $B_s \to K$ [46] form factors	
$f_0^{B_s}(q^2=0)$	$f_0^{B_d}(q^2=0)$
0.336 ± 0.023	0.332 ± 0.012

Relative errors: 6.8% numerator. 3.6% denominator

Assumptions

- We work in the QCDF framework.
- These deviations are assumed to be due to new short distance dynamics.
- These only affect the operators already present in the WET at the m_b scale.
- To start with, we further assume that such dynamics affects one operator at a time.
- As we will see, we will have to remove the previous assumption later on.

Operator basis and SM Wilson Coefficients

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p=c,u} \lambda_p^{(s,d)} \Big(\mathcal{C}^p_{1s,d} Q^p_{1s,d} + \mathcal{C}^p_{2s,d} Q^p_{2s,d} + \sum_{i=3\ldots10} \mathcal{C}_{is,d} Q_{is,d} + \mathcal{C}_{7\gamma s,d} Q_{7\gamma s,d} + \mathcal{C}_{8gs,d} Q_{8gs,d} \Big)$$

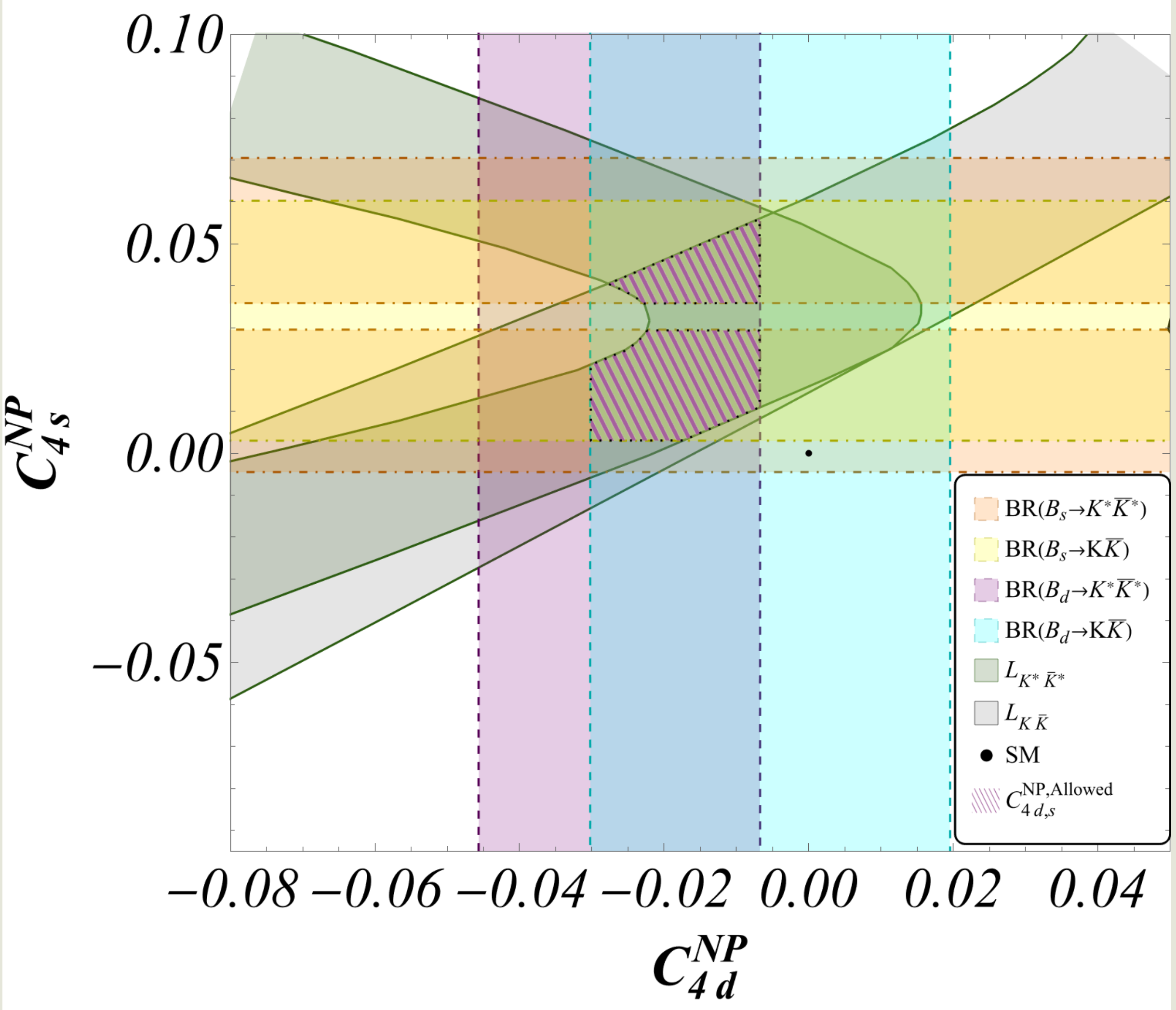
$$Q_{4f} = (\bar{f}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

$$Q_{8gf} = \frac{-g_s}{8\pi^2} m_b \, \bar{f} \sigma_{\mu\nu} (1+\gamma_5) G^{\mu\nu} b$$

$$Q_{6f} = (\bar{f}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}$$

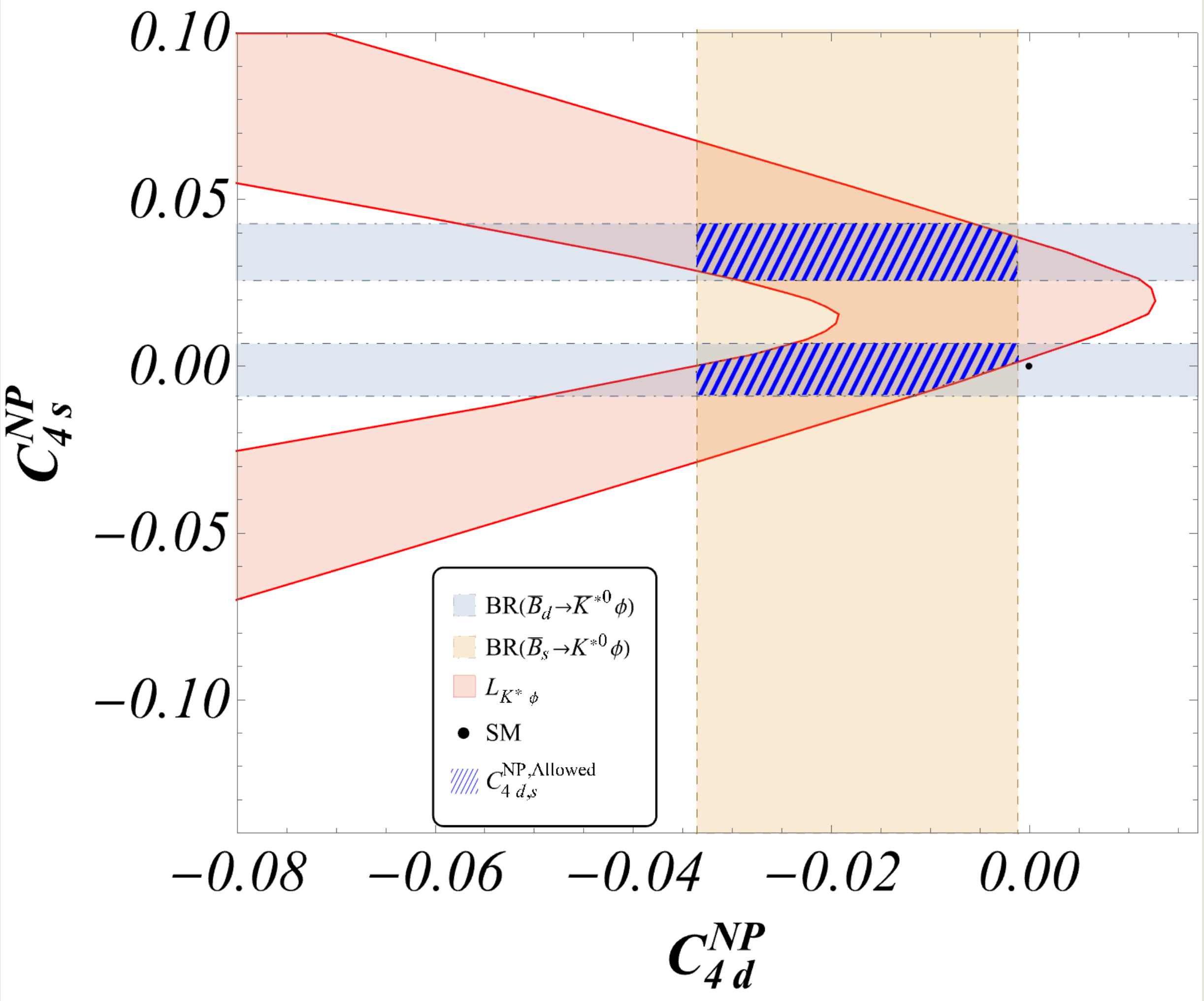
SM Wilson Coefficients (at $\mu = 4.18$ GeV)					
$\mathcal{C}_1$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{C}_4$	$\mathcal{C}_5$	$\mathcal{C}_6$
1.082	-0.191	0.014	-0.036	0.009	-0.042
$\mathcal{C}_7/\alpha_{em}$	$\mathcal{C}_8/\alpha_{em}$	$\mathcal{C}_9/\alpha_{em}$	$\mathcal{C}_{10}/\alpha_{em}$	$\mathcal{C}^{\text{eff}}_{7\gamma}$	$\mathcal{C}^{\text{eff}}_{8g}$
-0.011	0.060	-1.254	0.224	-0.318	-0.151

$C_{4d,s}^{NP}\ (\bar{B}_{d,s} \to K^{(*)}\bar{K}^{(*)})$

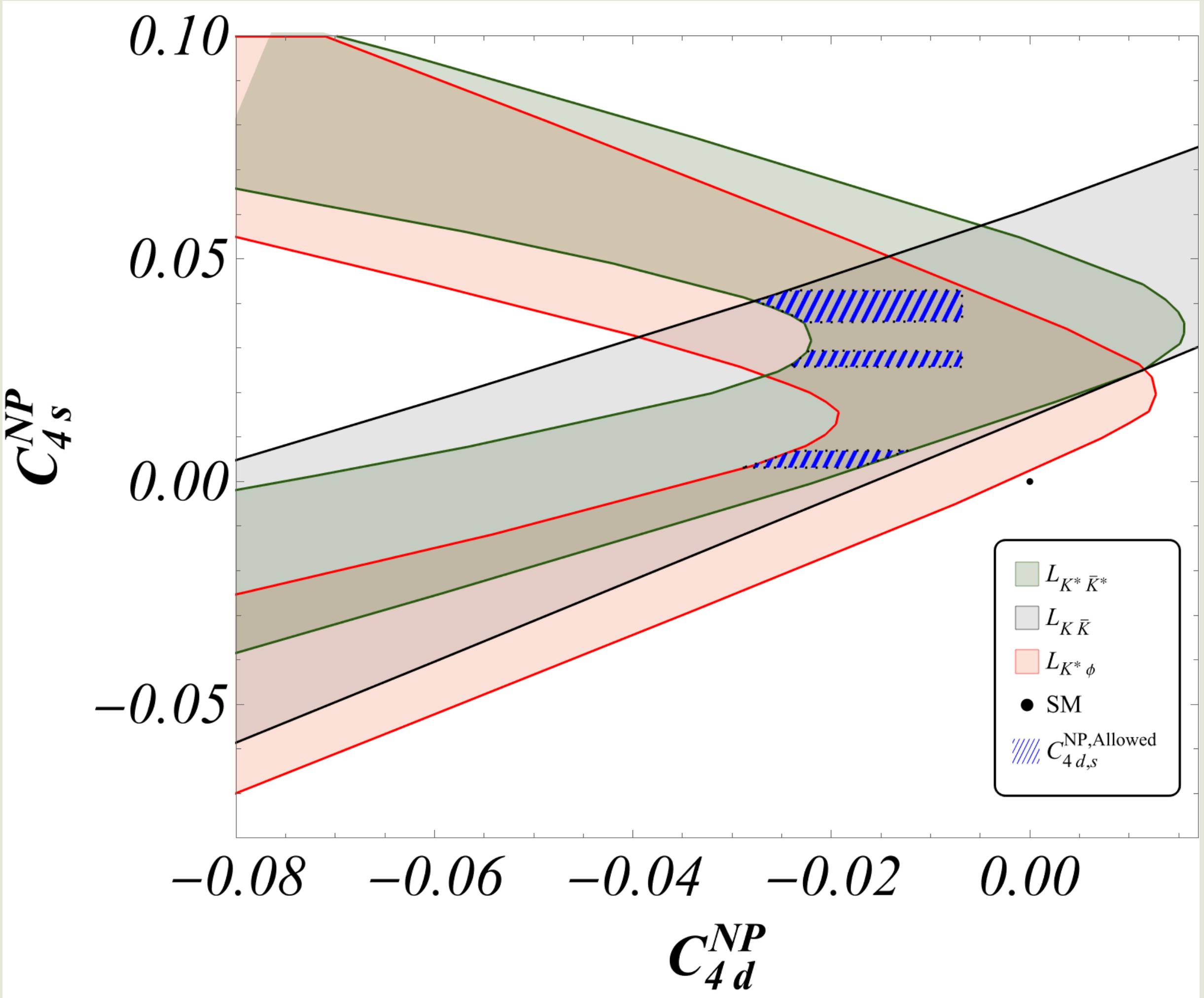


$$Q_{4f} = (\bar{f}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

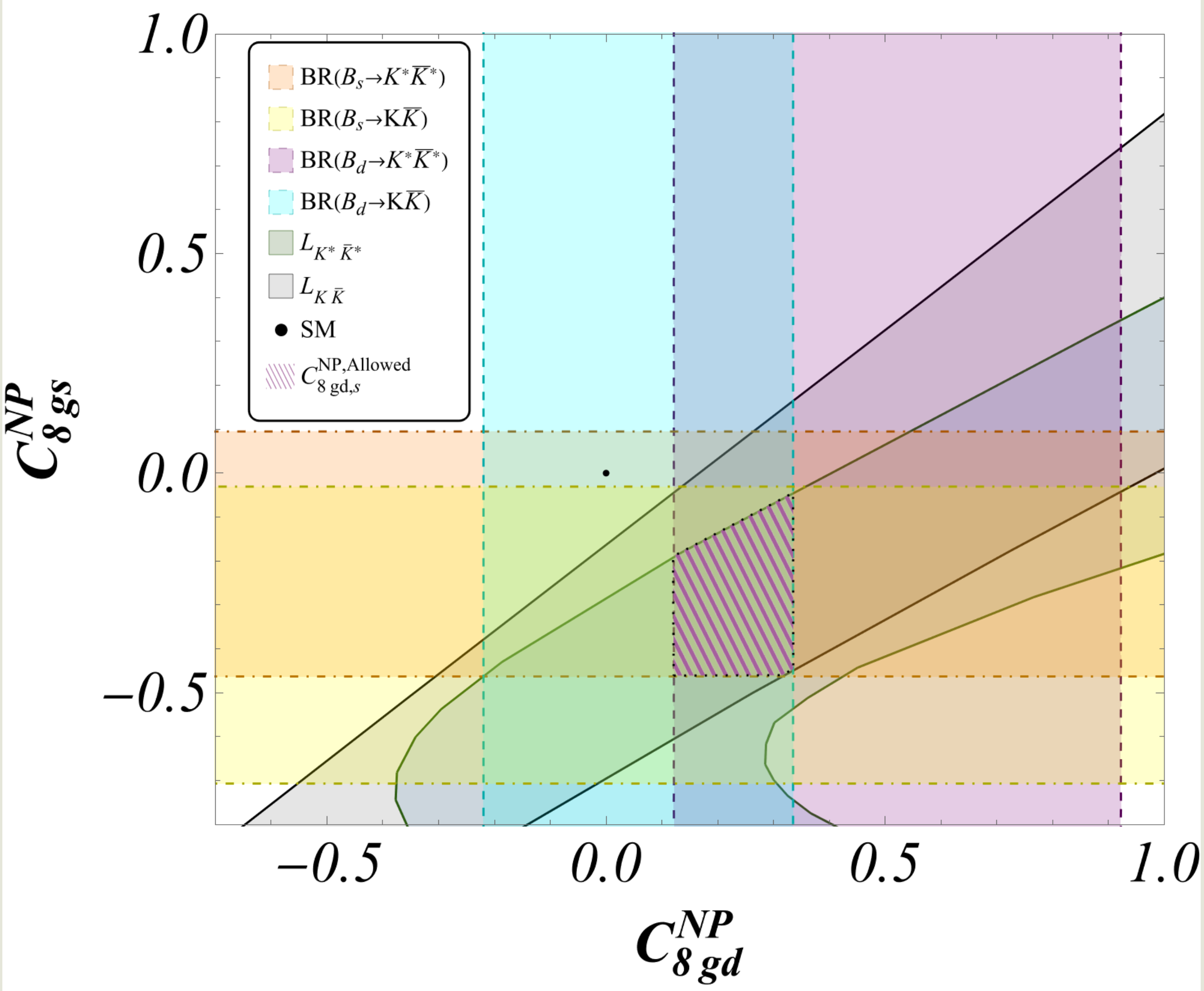
$C_{4d,s}^{NP}\ (\bar{B}_{s,(d)} \to \mathrm{K}^*(\bar{K}^*)\phi)$



$C_{4d,s}^{NP}$ (PP, VV combined)

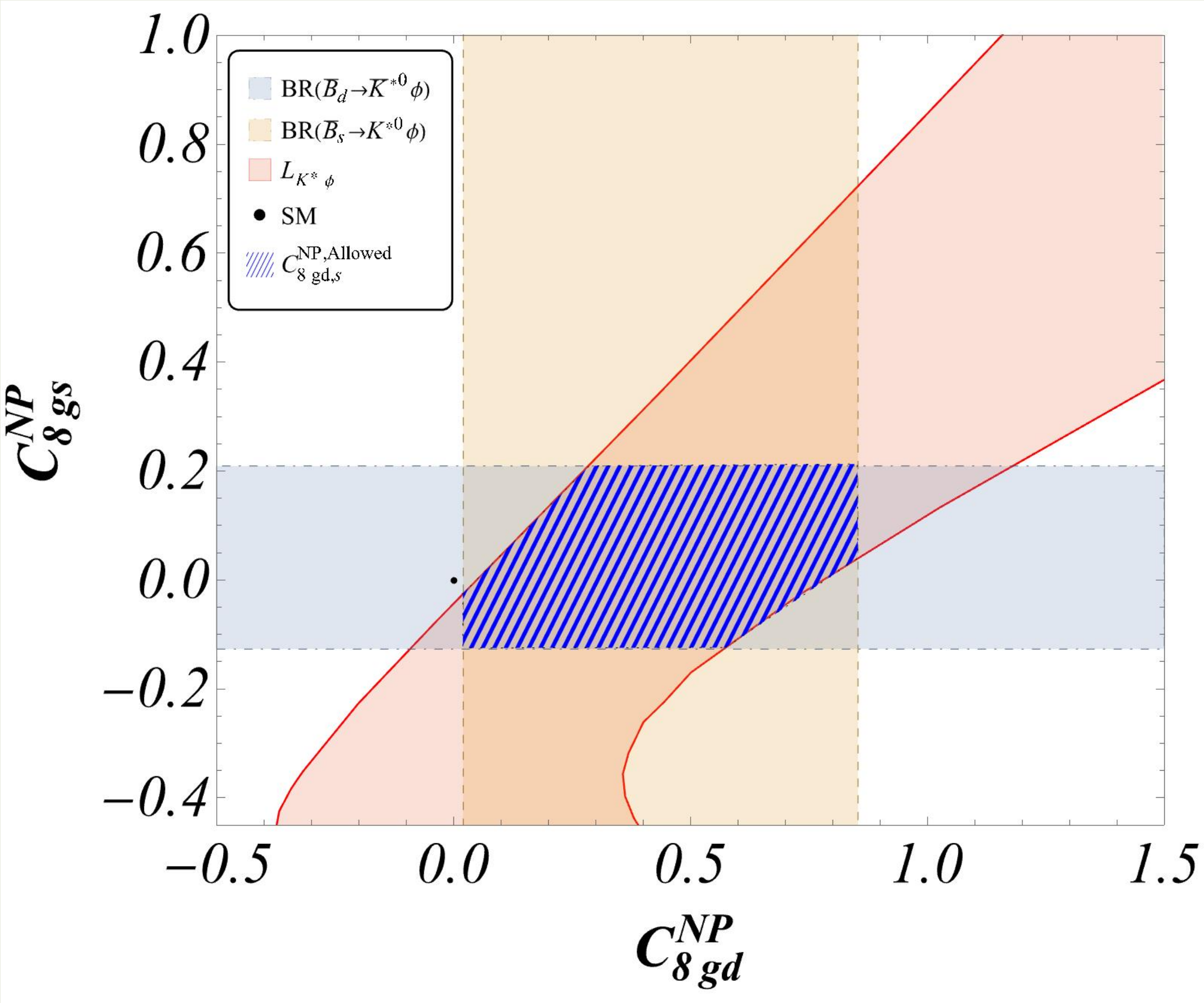


$C_{8gd,s}^{NP}\ (\bar{B}_{d,s} \to \mathrm{K}^{(*)}\bar{K}^{(*)})$

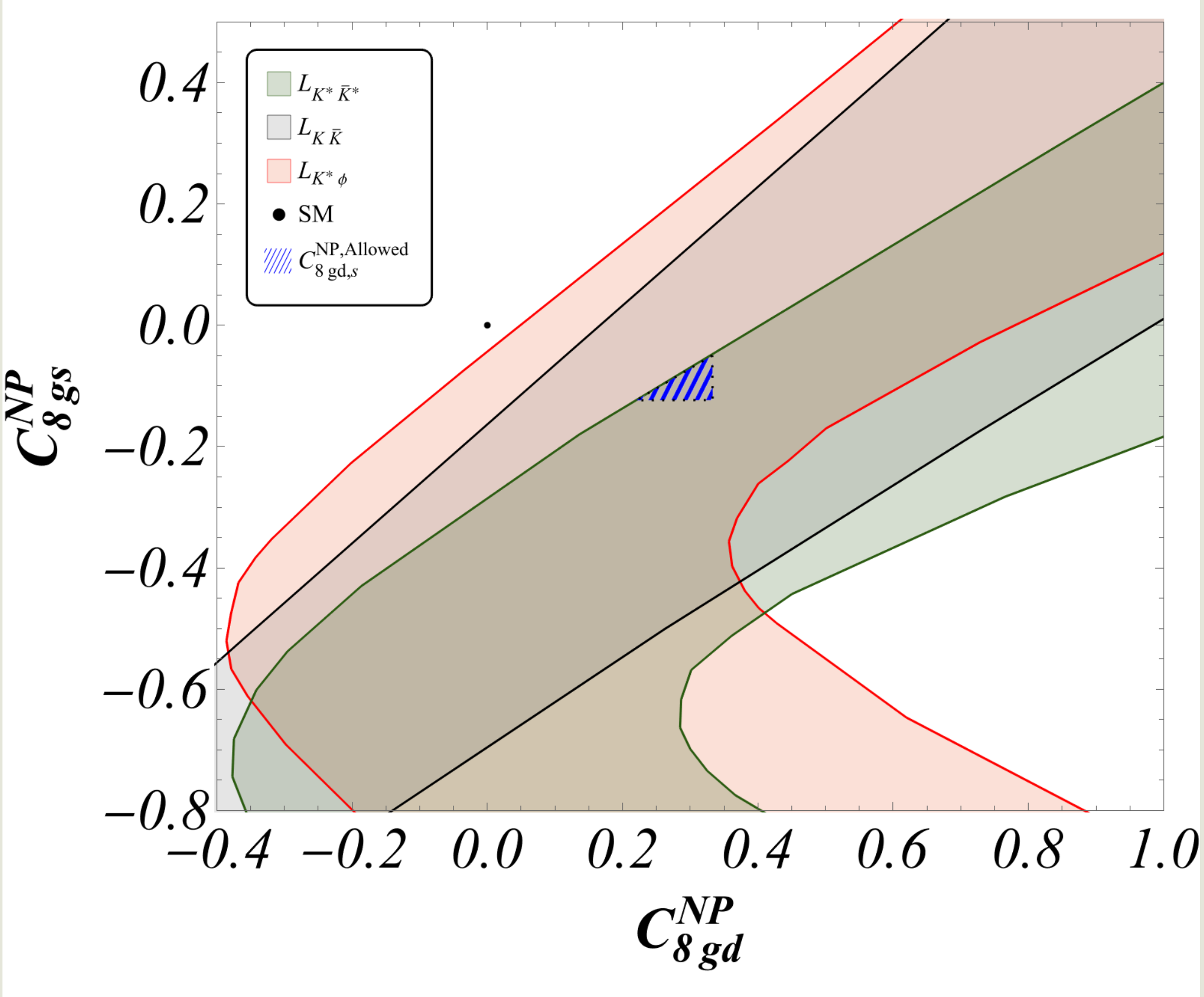


$$Q_{8gf} = \frac{-g_s}{8\pi^2}\, m_b\, \bar{f}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu} b$$

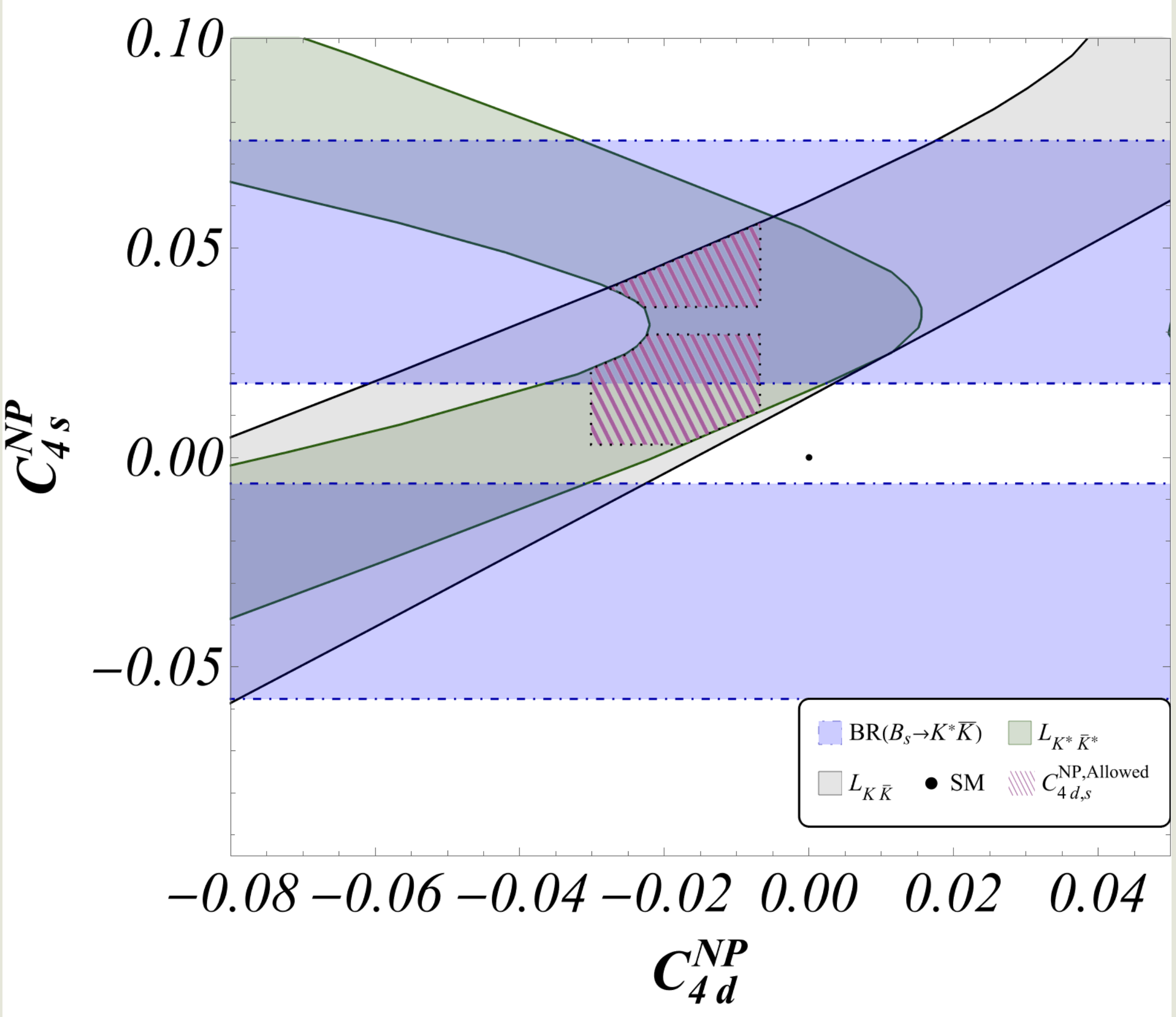
$C^{NP}_{8gd,s}(\bar{B}_{s,(d)} \to K^*(\bar{K}^*)\phi)$

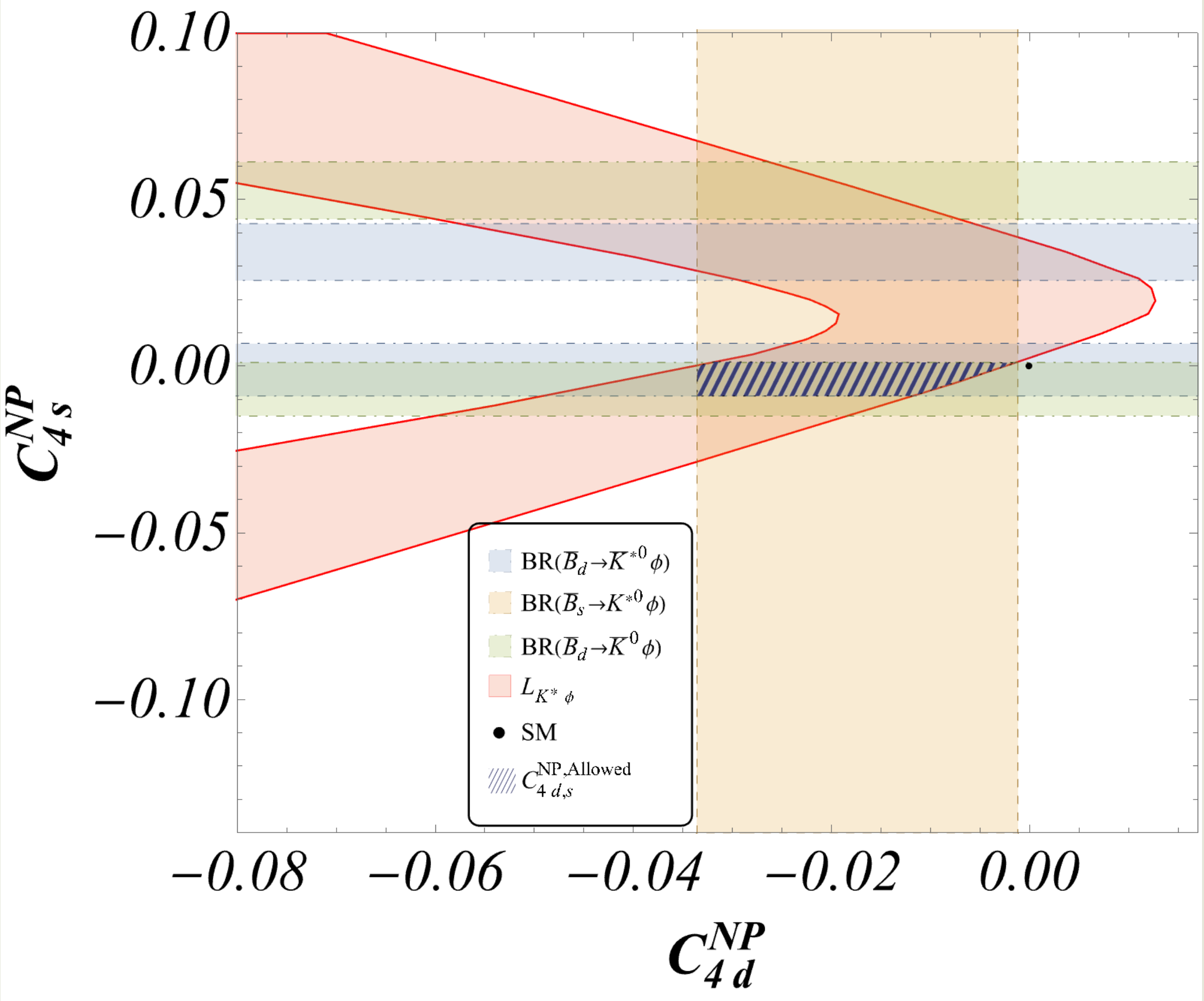


$C^{NP}_{8gd,s}(PP, VV\ combined)$

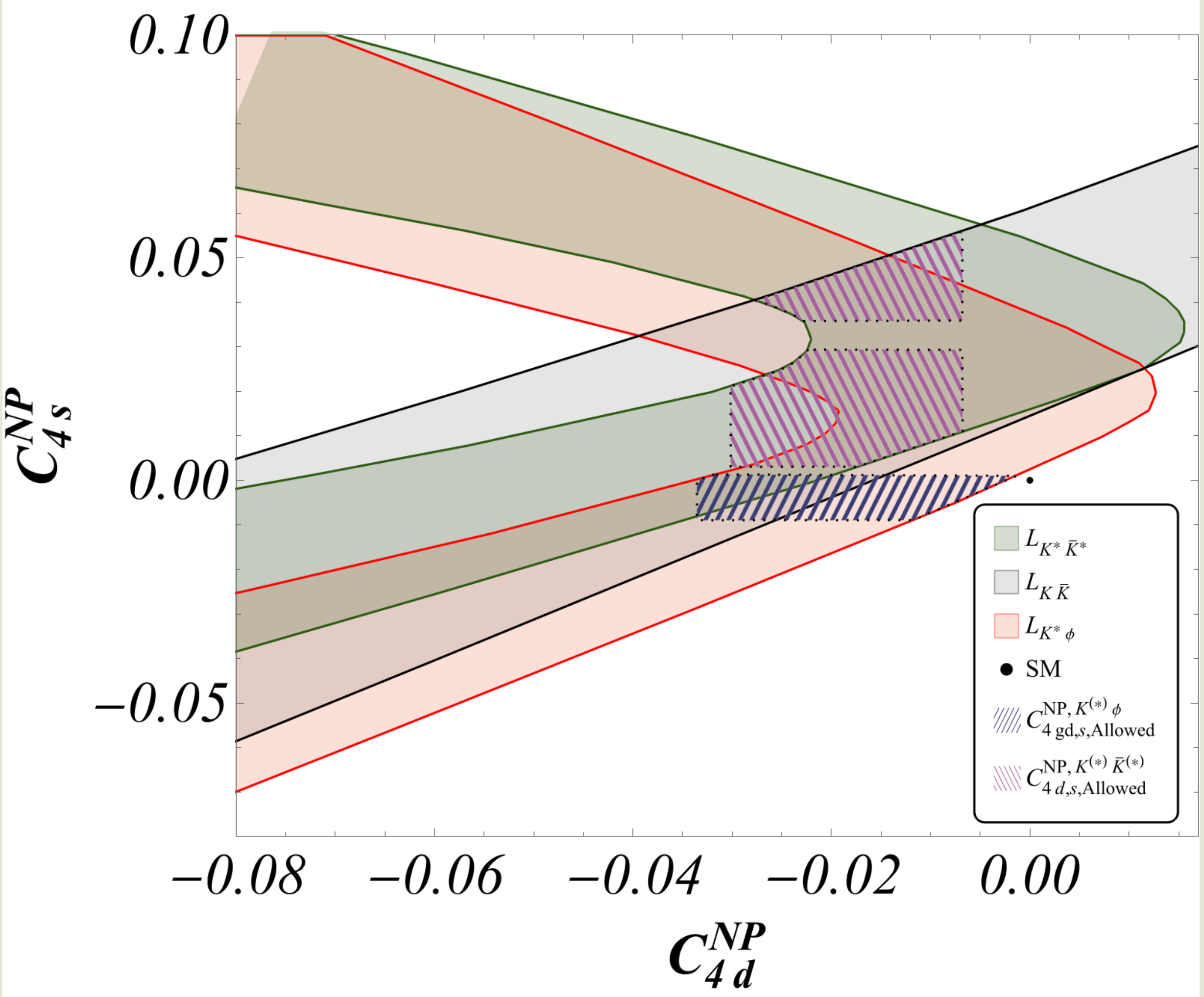


Effect of the mixed modes ($\bar{B}_s \to K^*\bar{K} + c.c.$) and ($\bar{B}_d \to \bar{K}\phi$) on $C^{NP}_{4d,s}$ plane

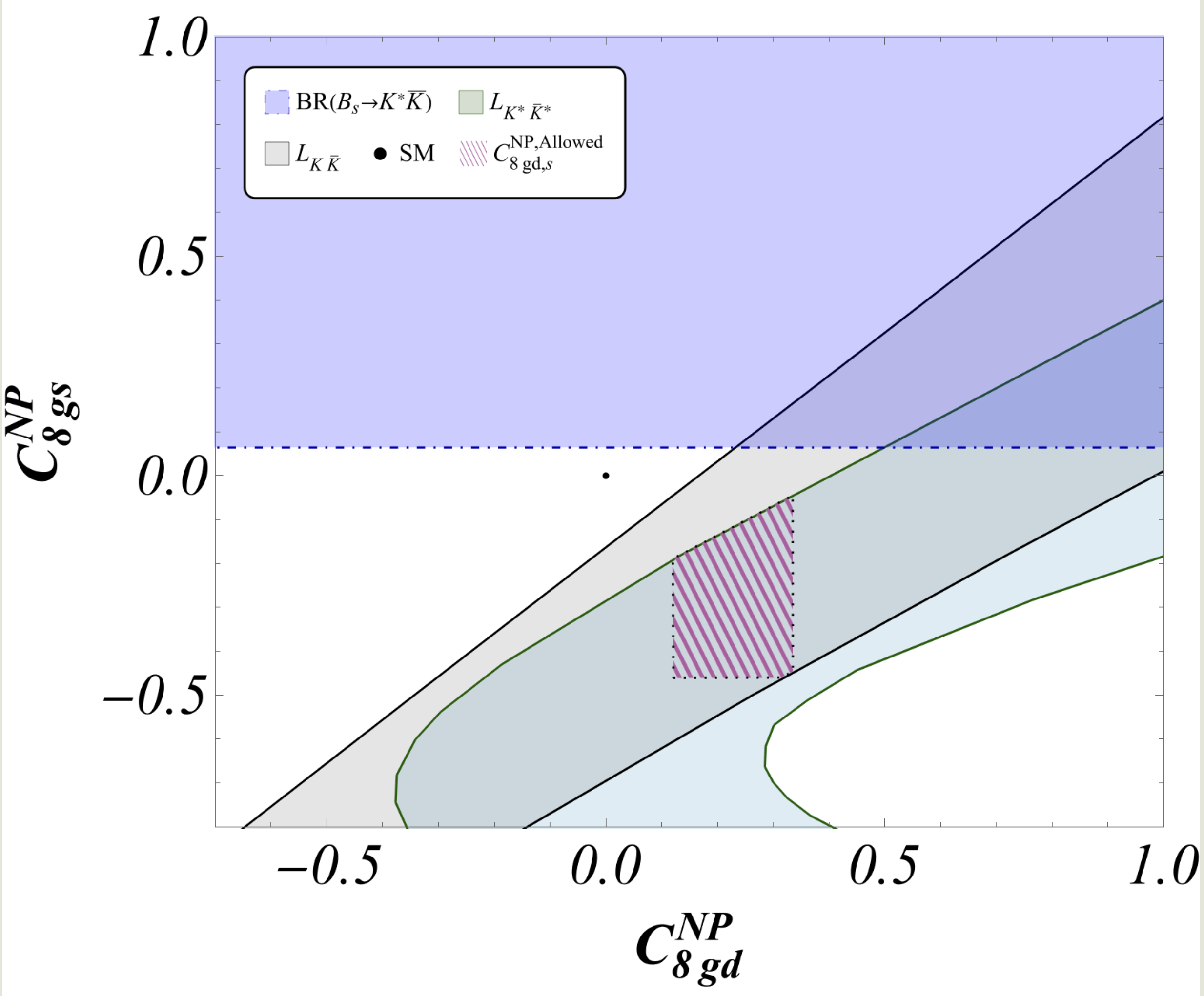


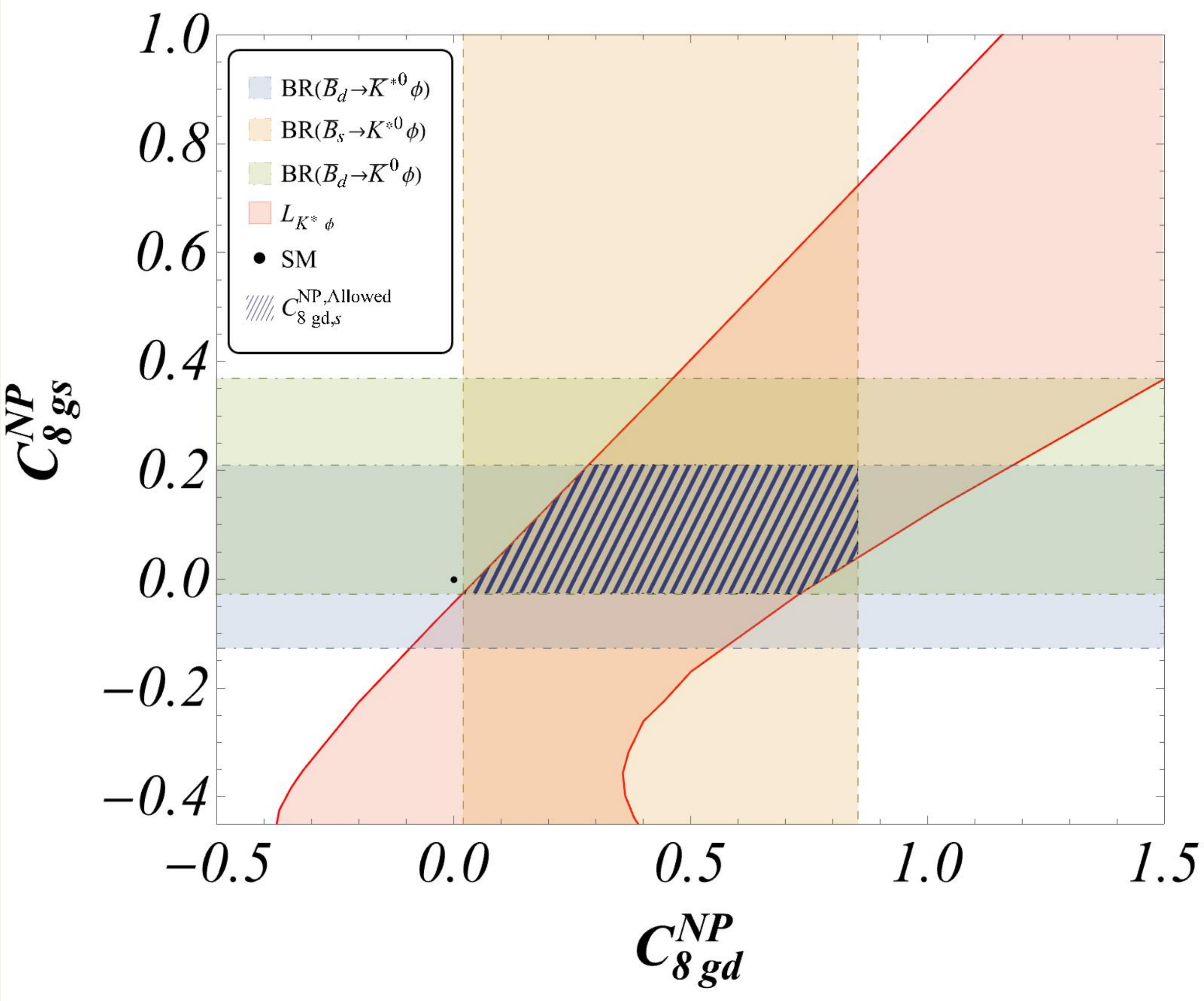


Effect of the mixed modes ($\bar{B}_s \to K^* \bar{K} + c.c.$) and ($\bar{B}_d \to \bar{K}\phi$) on $C^{NP}_{4d,s}$ plane

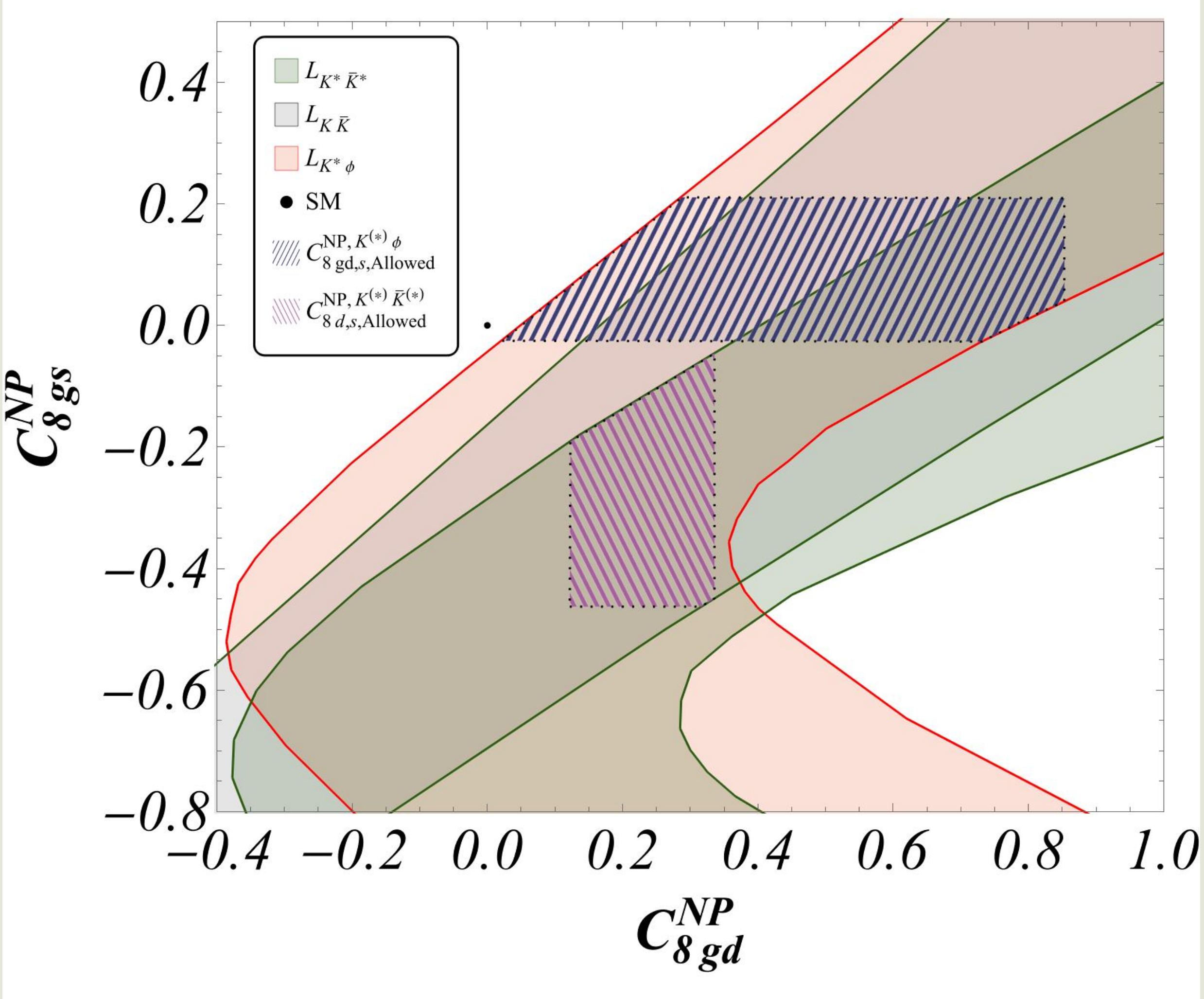


Effect of the mixed modes ($\bar{B}_s \to K^* \bar{K} + c.c.$) and ($\bar{B}_d \to \bar{K}\phi$) on $C^{NP}_{8gd,s}$ plane





Effect of the mixed modes ($\bar{B}_s \to K^* \bar{K} + c.c.$) and ($\bar{B}_d \to \bar{K}\phi$) on $C^{NP}_{8gd,s}$ plane



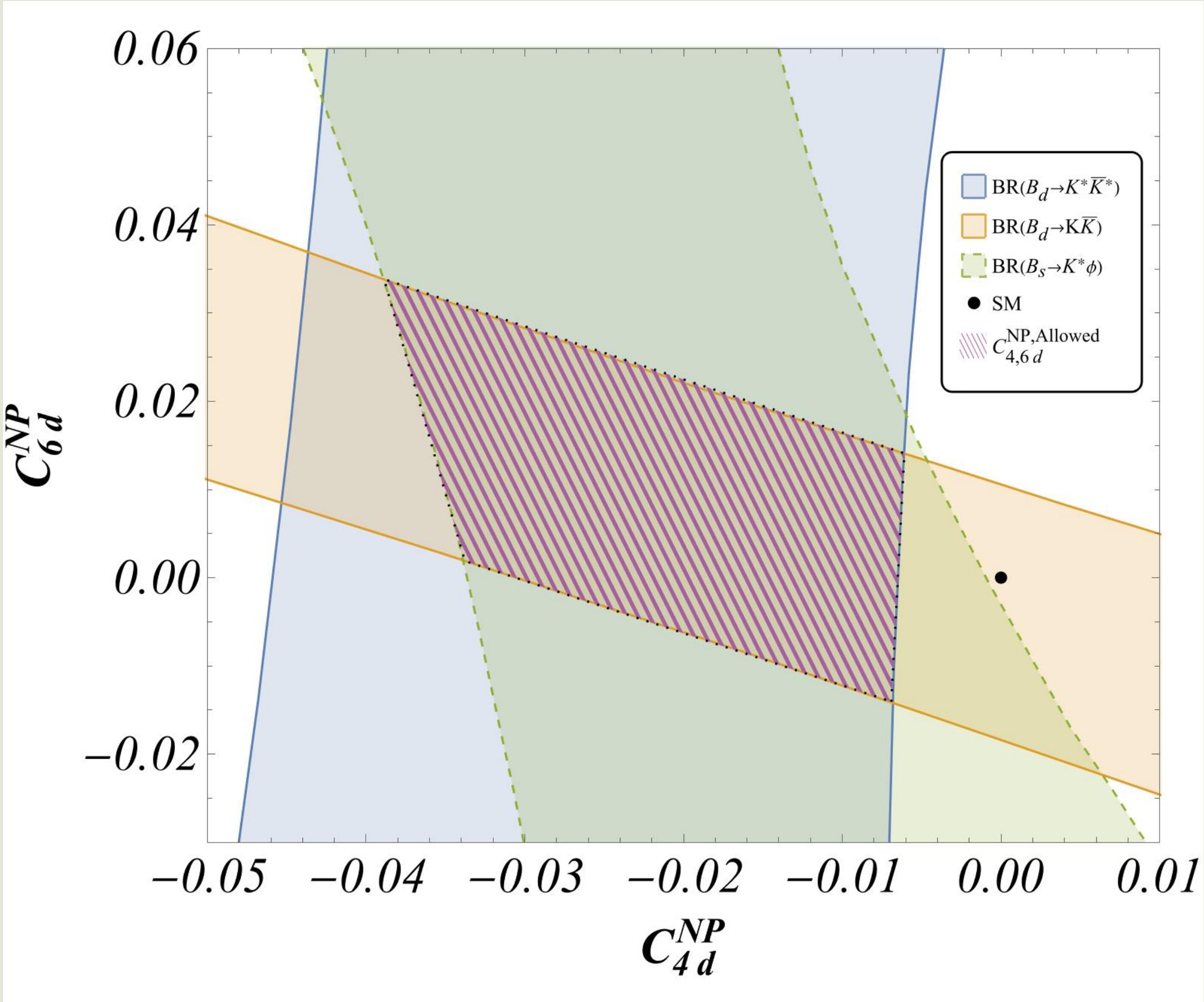
Recap: Lessons from one operator scenarios

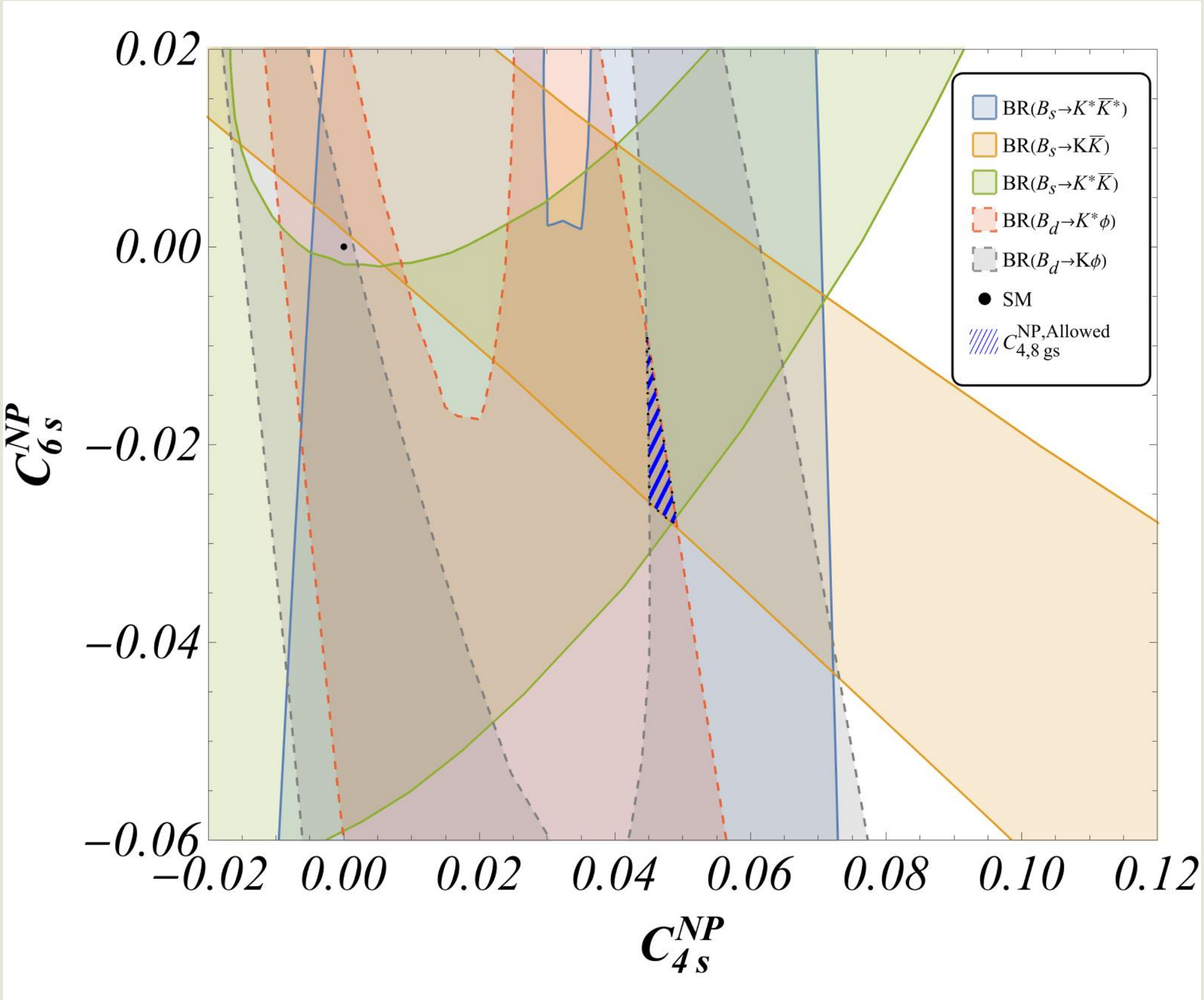
- Assuming NP affects either $Q_{4d,s}$ or $Q_{8gd,s}$ we find common overlaps for PP and VV modes.
- Result of including $K^*\phi$ modes with $K^{(*)}K^{(*)}$modes is that the "allowed" range of NP values is greater for $b \to d$ as compared to $b \to s$.
- This pattern is broken when one includes the branching ratios for the pseudoscalar-vector modes.
- Assuming NP affects $Q_{4d,s}$, one finds overlaps separately among $K\phi$ & $K^*\phi$ and $K^*K + c.c.$ & $K^{(*)}K^{(*)}$ modes but not together.
- Assuming NP affecting $Q_{8gd,s}$, simultaneous overlap of $K^{(*)}\phi$ is possible but not for $K^*K + c.c.$ with $K^{(*)}K^{(*)}$.
- No common one operator explanation is possible. **Two operators $(\textbf{involving } Q_6)$?!**

Two operator scenarios: Algorithm

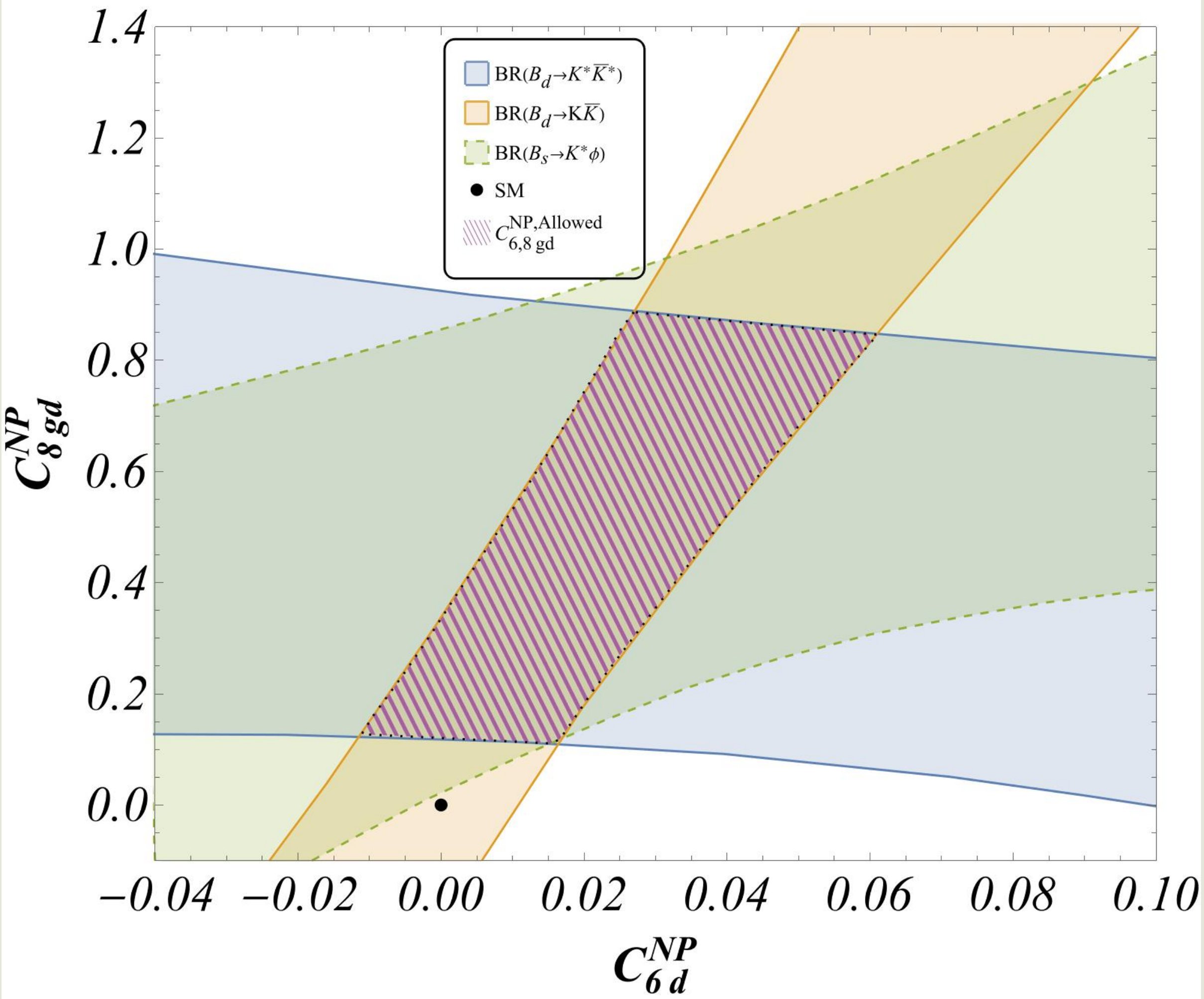
- Assuming NP affects two $(b \to s, d)$ operators, the L observable depends on 4 NP Wilson coefficients and cannot be represented in a 2-D plane.
- However, the branching ratios now depend on 2 parameters and can be represented in 2-D plots.
- Prepare a grid for $b \to s, d$ NP Wilson coefficients $\left(C_{is,d}, C_{js,d}\right)$ for the scenario $Q_{is,d} - Q_{js,d}$ and look for values that explain $L_{K^{(*)}K^{(*)}}$ and $L_{K^*\phi}$ simultaneously. This will essentially result in a list of quadruplets $[C_{is}, C_{js}, C_{id}, C_{jd}]$.
- Now find regions of common overlap among the $b \to s$ and $b \to d$ branching ratios in the corresponding 2-D planes separately, if any.
- Overlay the $C_{4s(d)}, C_{8gs(d)}$ couplets from the quadruplets on the 2-D $b \to s(d)$ plot and identify those that fall on the common regions.
- Identify the quadruplets which the couplets falling in the common region correspond to. These quadruplets are the sets of Wilson coefficients that explain all the L's and branching ratios simultaneously.

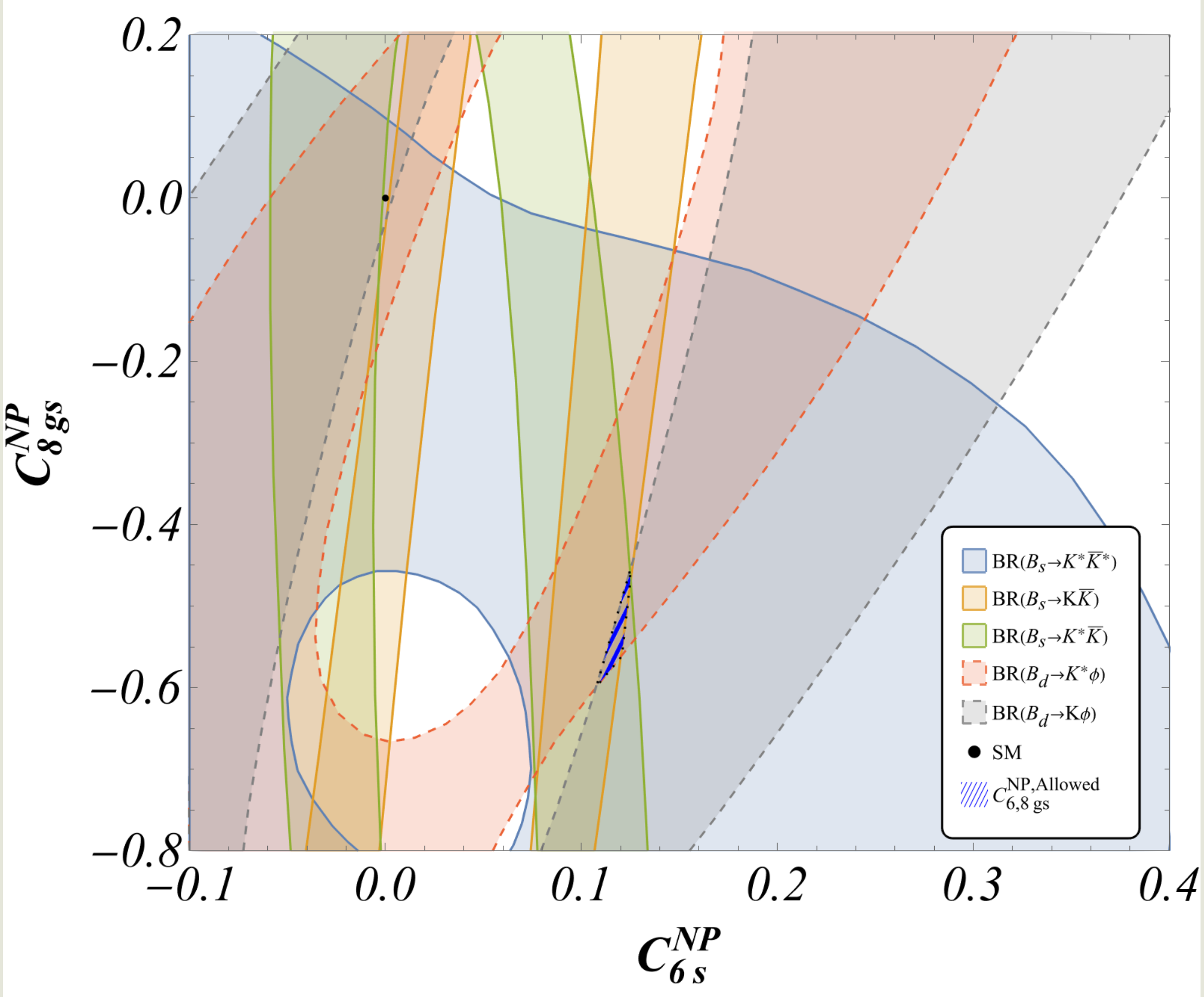
Two operator scenarios: $Q_4 - Q_6$



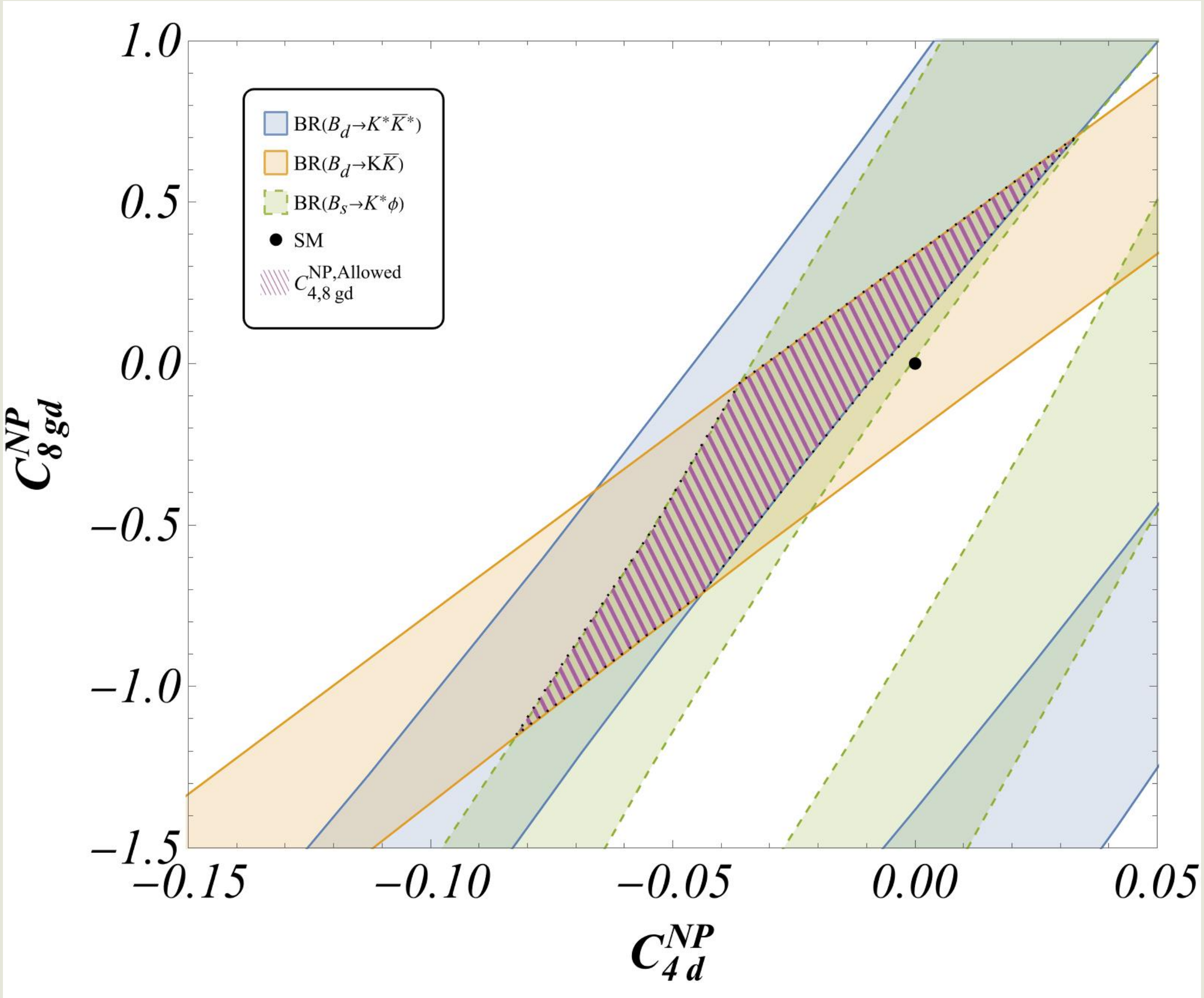


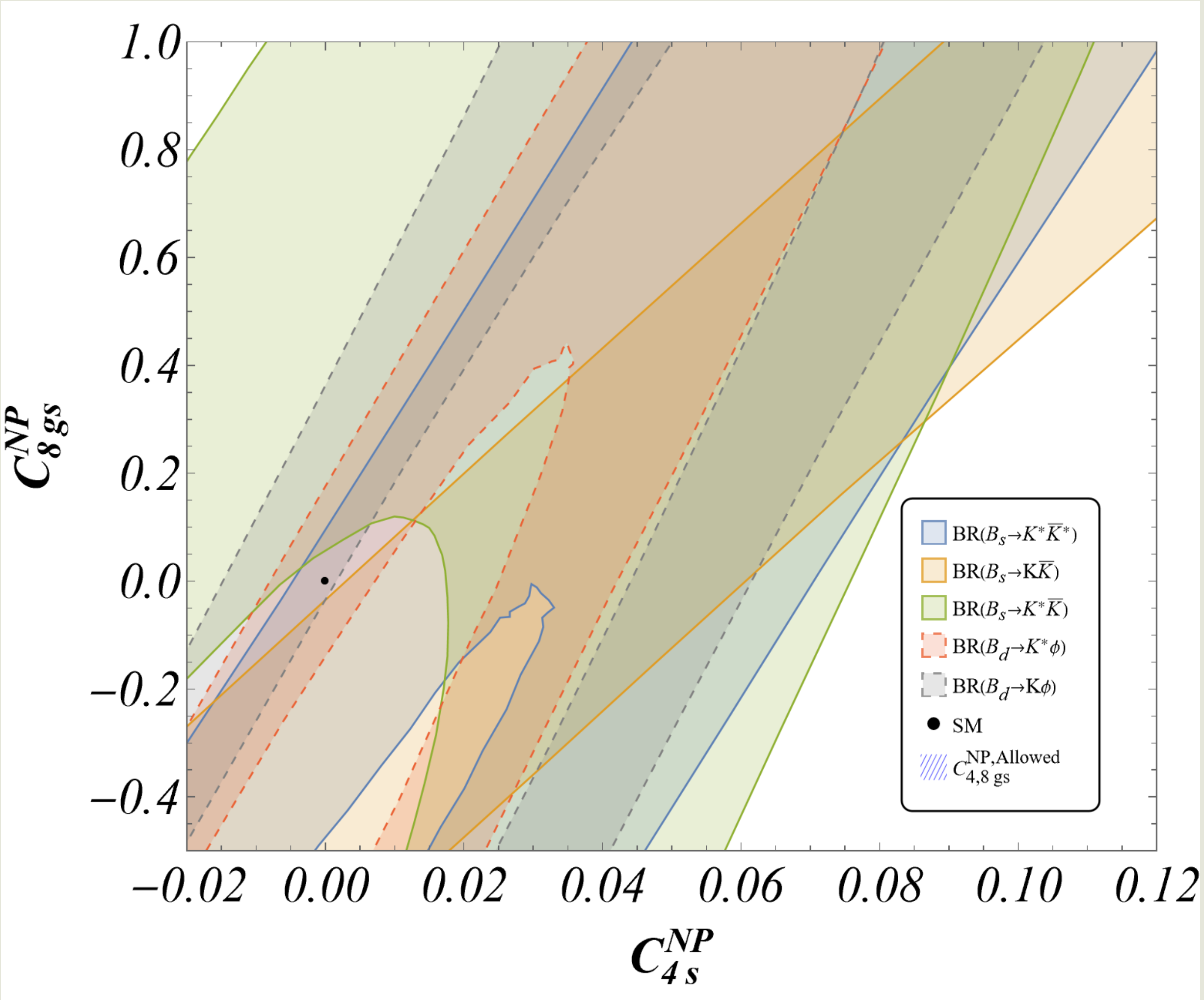
Two operator scenarios: $Q_6 - Q_{8g}$



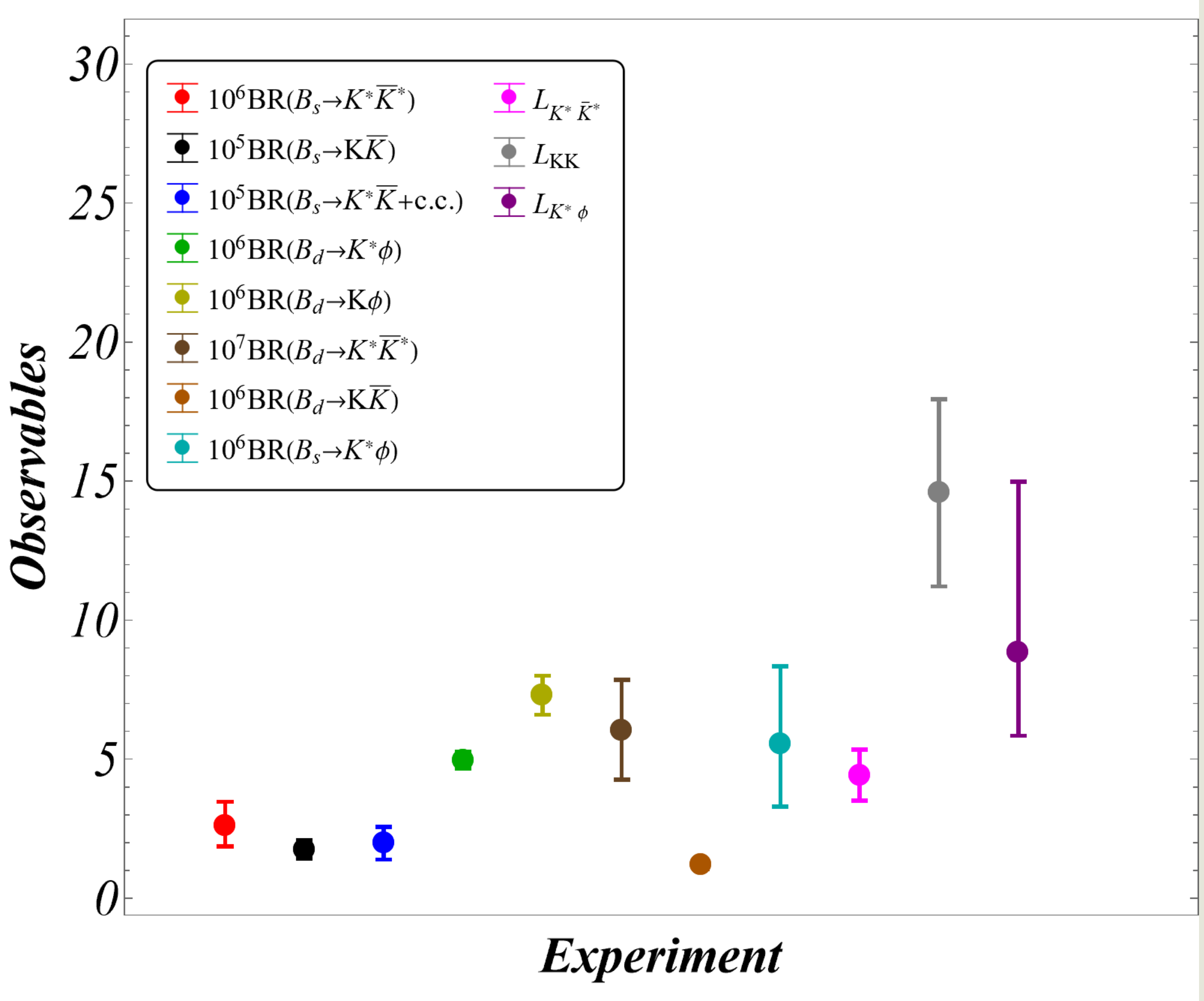


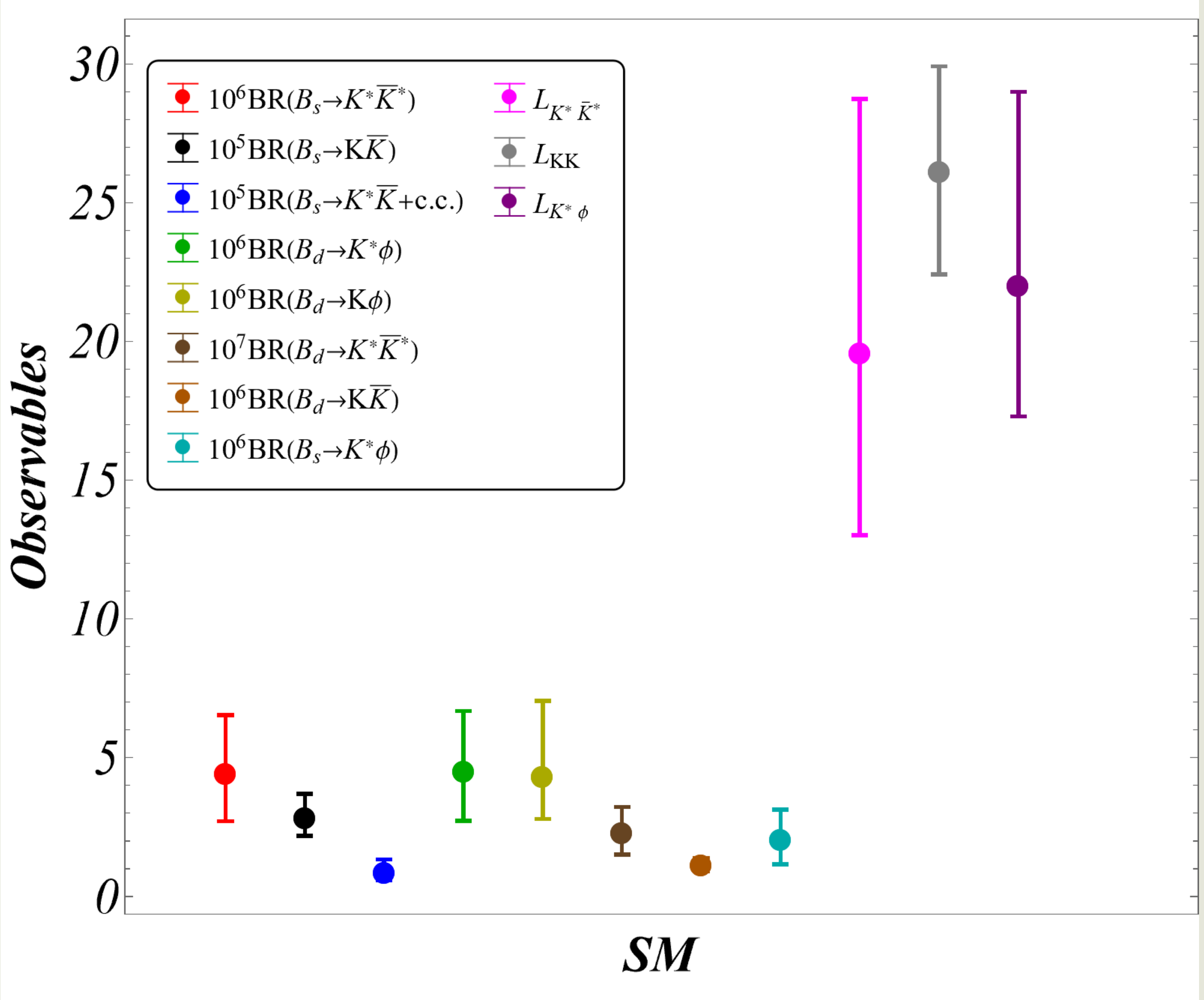
Two operator scenarios: $Q_4 - Q_{8g}$



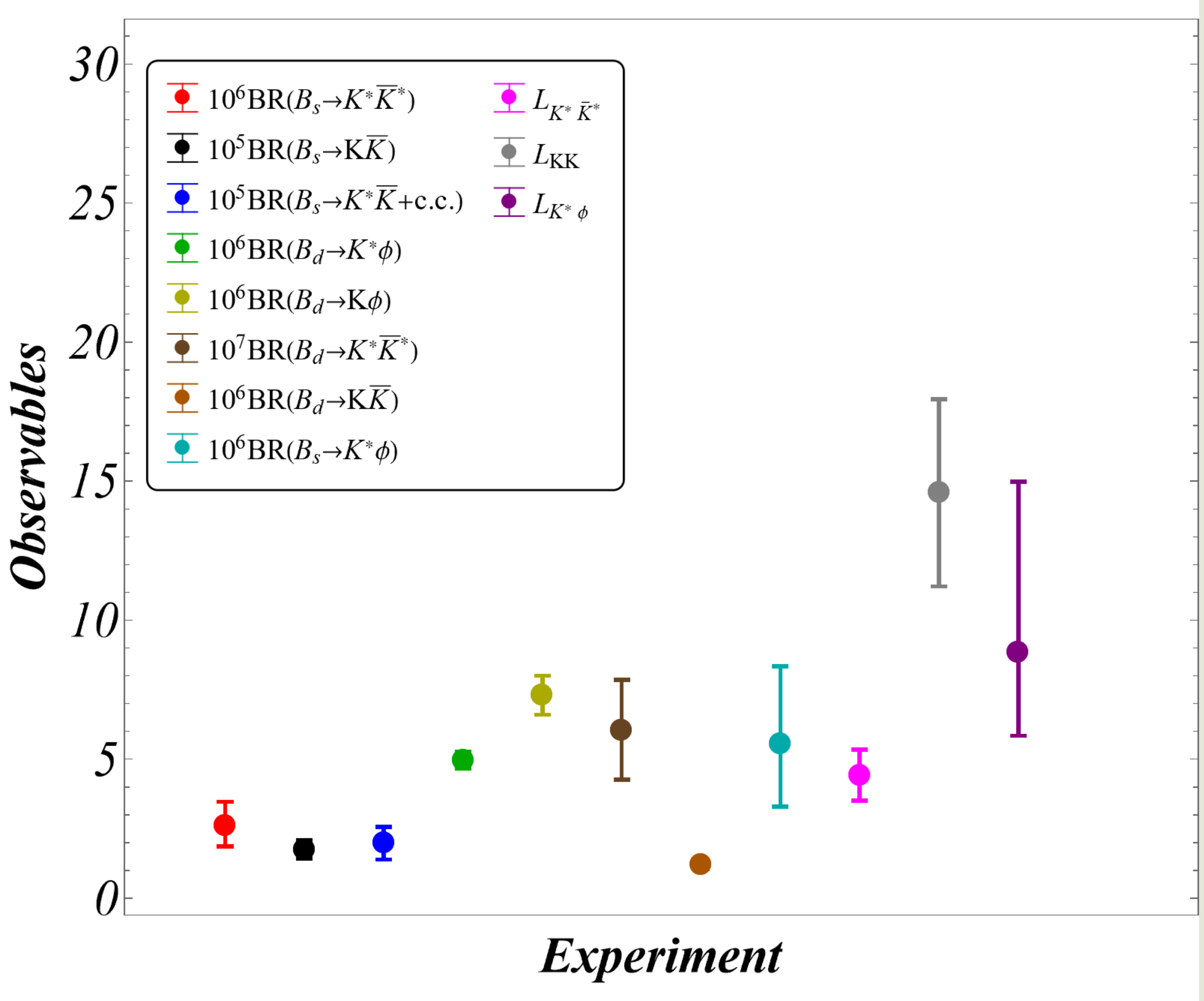


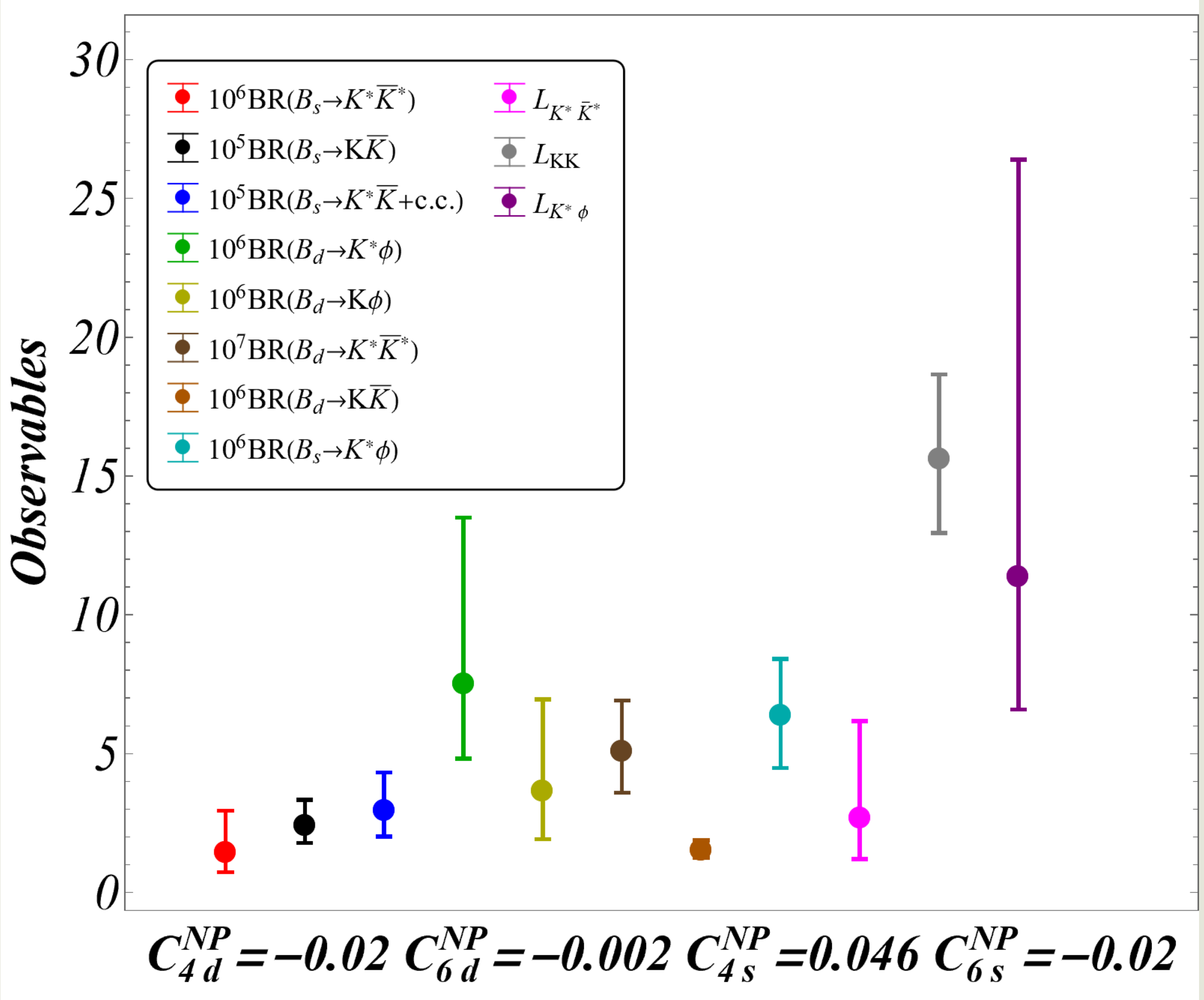
Comparison: SM



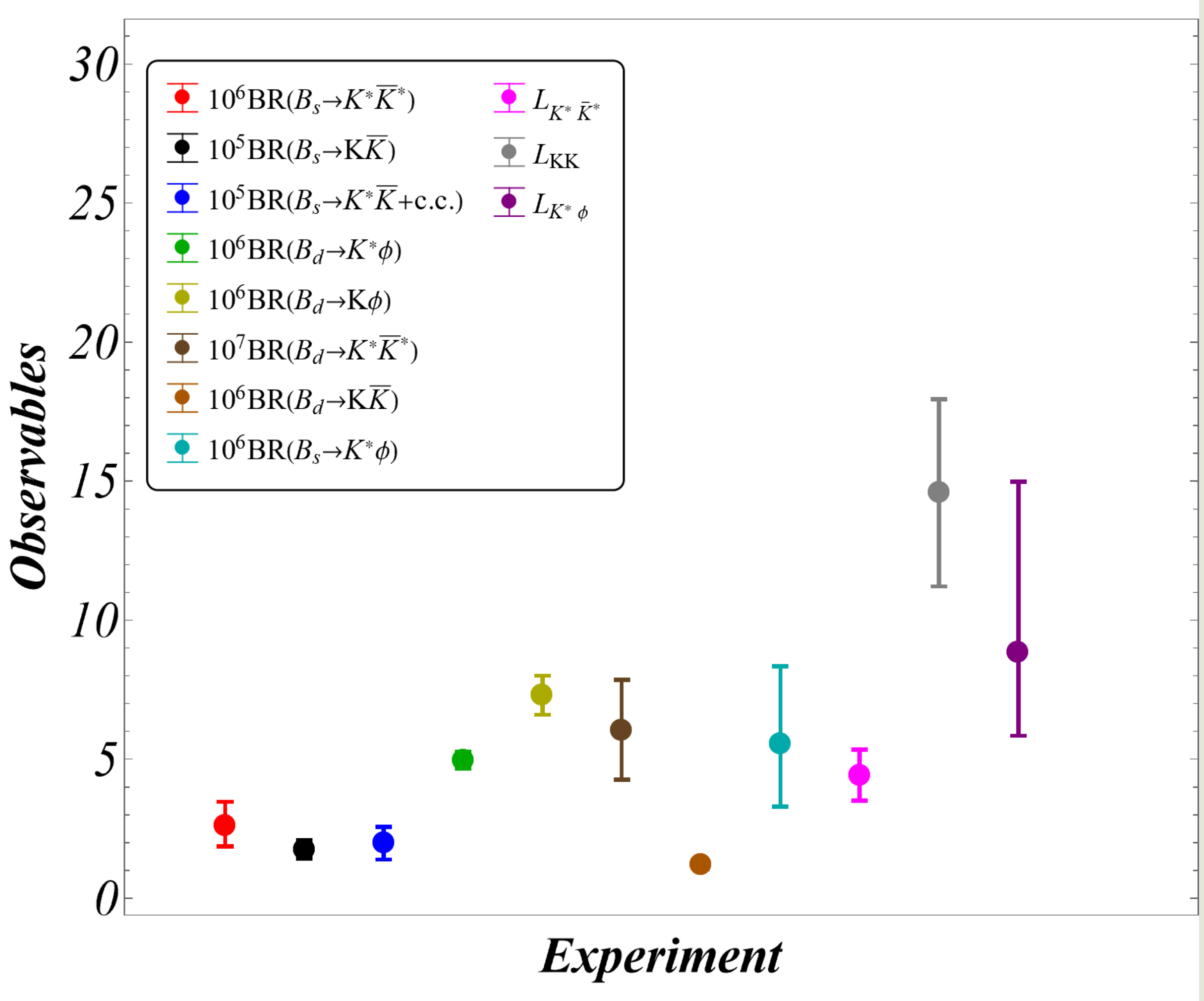


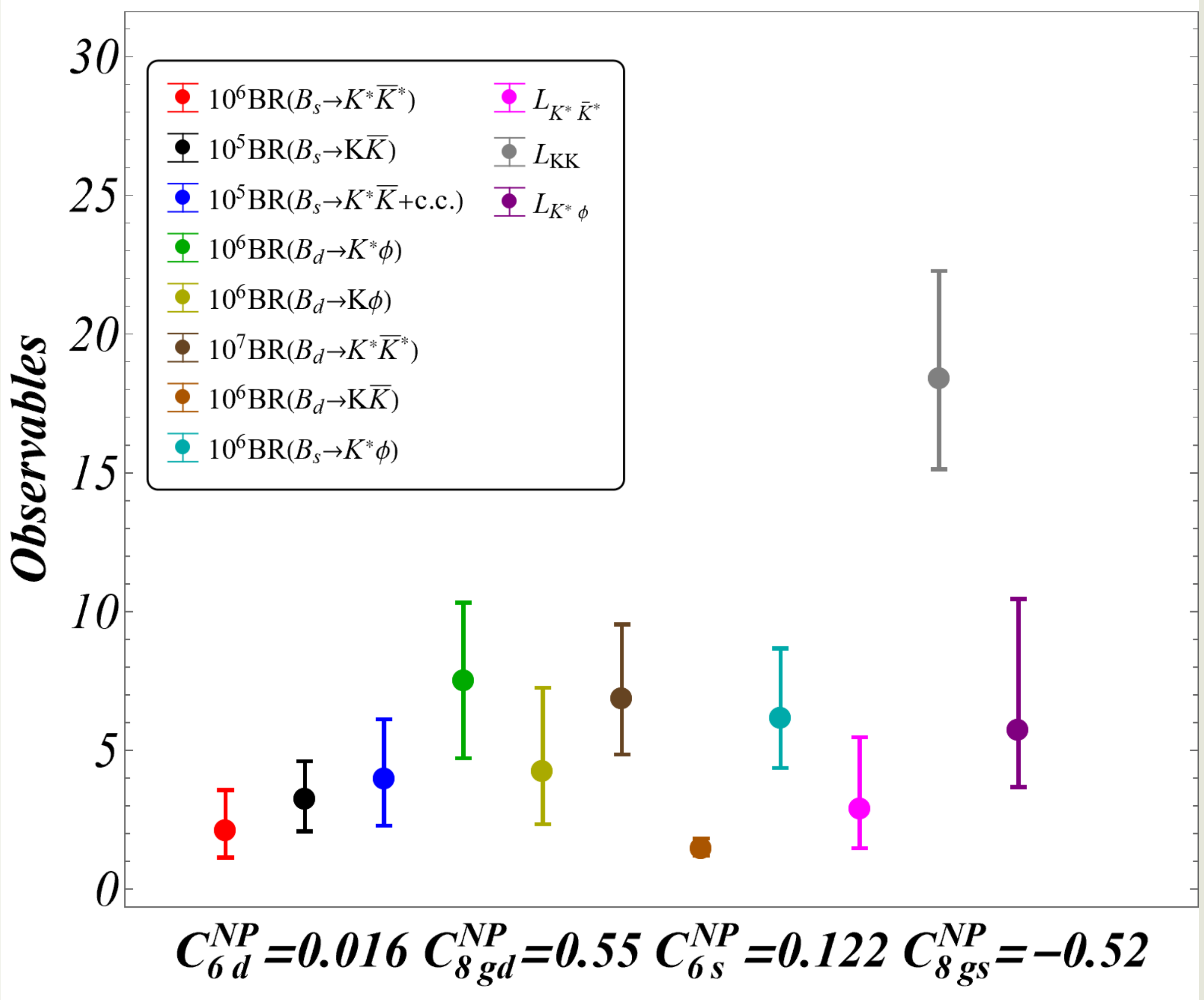
Comparison: $Q_4 - Q_6$



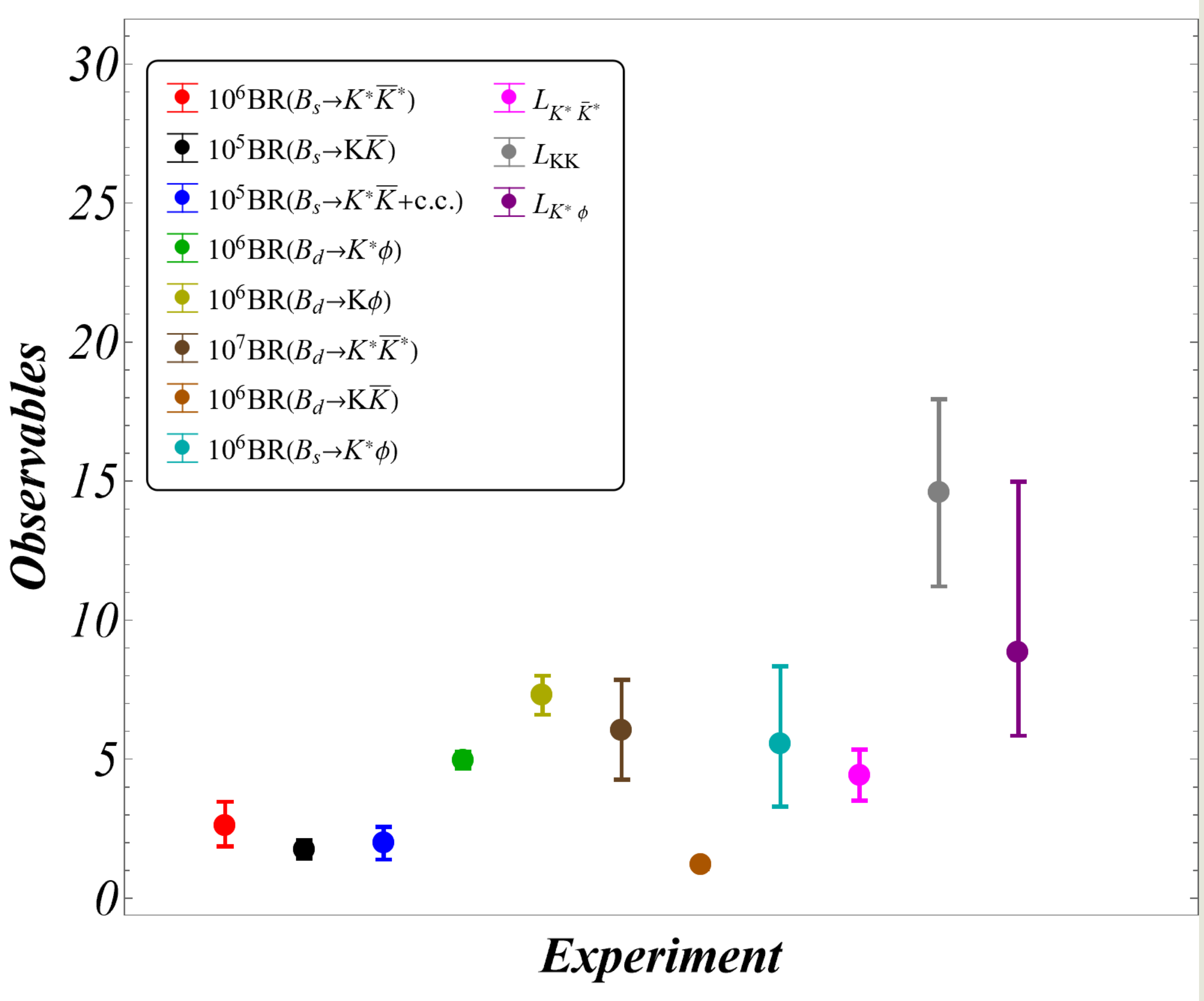


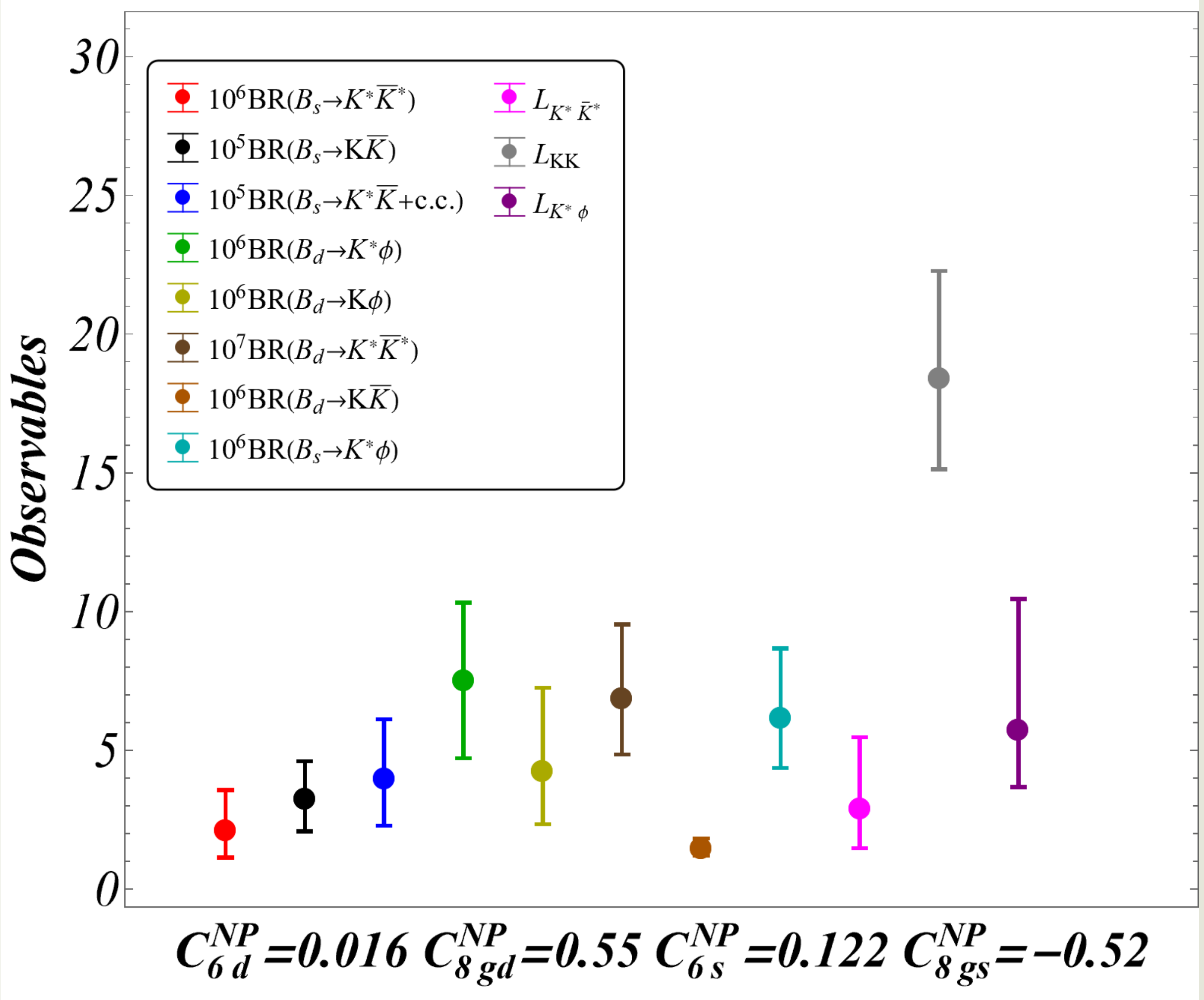
Comparison: $Q_6 - Q_{8g}$





Comparison: $Q_6 - Q_{8g}$





Conclusions

- Proposed optimized "L" observables which are ratios involving penguin dominated decay modes related by a d to s transition: only used while modelling the divergent annihilation and hard spectators.
- Dominant sources of uncertainties for theoretical SM estimates of the L's are form factors .
- All the VV, PP L's and branching ratios have overlaps assuming NP affects either $Q_{4d,s}$ or $Q_{8gd,s}$.
- However, the inclusion of the currently measured VP modes ruin this setup.
- The simplest NP scenarios that result in common overlap among all the VV, PP and PV branching ratios along with the three L's are 2 operator scenarios $Q_{4f} - Q_{6f}$ and $Q_{6f} - Q_{8gf}$.
- $Q_{6d,s}$ is important!

Future directions and discussons

- Correlated form factors (LCSR)?
- Correlated measurement of Branching fractions (LHCb is already working on these modes: Last talk yesterday by Ben and Davide).
- New ways of tackling annihilations: Fits. Breaking of unitarity. Analysis ongoing.
- Beyond Beneke etal: Symmetries and symmetry breakings. CP asymmetry measurements.
- $L_{K^*\phi}^{exp}$ has asymmetric errors. However, a correlated measurement in the future, as well as an increase in the precision of $f_L(\bar{B}_s \to K^{*0}\phi)$ and $BR(\bar{B}_s \to K^{*0}\phi)$ will help decrease the asymmetry.
- Measurement on $BR(\bar{B}_d \to \bar{K}^0\phi)$ from both Belle and Babar are more than two and one decades old respectively. Maybe updated measurement can change this scenario.
- Measurement on $b \to d$ $BR(\bar{B}_s \to K^0\phi)$ and $BR(\bar{B}_d \to K^{*0}\bar{K}^0 + c.c.)$. Will permit construction of L's for mixed modes.
- First exploratory works. Working on rigorous statistical analysis taking asymmetric distributions into account: Stay tuned!

THANK YOU!

Backup

$B_{d,s}$ Distribution Amplitudes (at $\mu = 1$ GeV) [34, 35]		
λ_{B_d} [GeV]	$\lambda_{B_s}/\lambda_{B_d}$	σ_B
0.383 ± 0.153	1.19 ± 0.14	1.4 ± 0.4

K^* Distribution Amplitudes (at $\mu = 2$ GeV) [36]			
$\alpha_1^{K^*}$	$\alpha_{1,\perp}^{K^*}$	$\alpha_2^{K^*}$	$\alpha_{2,\perp}^{K^*}$
0.02 ± 0.02	0.03 ± 0.03	0.08 ± 0.06	0.08 ± 0.06

ϕ Distribution Amplitudes (at $\mu = 2$ GeV) [36]			
α_1^{ϕ}	$\alpha_{1,\perp}^{\phi}$	α_2^{ϕ}	$\alpha_{2,\perp}^{\phi}$
0	0	0.13 ± 0.06	0.11 ± 0.05

Decay Constants for B mesons (at $\mu = 2$ GeV) [37] and K meson [28]		
f_{B_d}	f_{B_s}/f_{B_d}	f_K
0.190 ± 0.0013	1.209 ± 0.005	0.1557 ± 0.0003

Decay Constants for K^*, ϕ, ρ, ω (at $\mu = 2$ GeV) [26, 38]					
f_{K^*}	$f_{K^*}^{\perp}/f_{K^*}$	f_ϕ	$f_\phi^{\perp}/f_\phi$	f_ρ	f_ω
0.204 ± 0.007	0.712 ± 0.012	0.233 ± 0.004	0.750 ± 0.008	0.213 ± 0.005	0.197 ± 0.008

$B_{d,s} \to K^*, \phi$ form factors [26] and B-meson lifetimes (ps) [39]				
$A_0^{B_s \to K^*}(q^2 = m_\phi^2)$	$A_0^{B_d \to K^*}(q^2 = m_\phi^2)$	$A_0^{B_s \to \phi}(q^2 = m_{K^*}^2)$	τ_{B_d}	τ_{B_s}
0.380 ± 0.024	0.393 ± 0.039	0.438 ± 0.024	1.519 ± 0.004	1.520 ± 0.005

Mass and decay widths for ρ, ω (GeV) [28]			
m_ρ	Γ_ρ	m_ω	Γ_ω
0.7745	0.1484	0.7827	0.0087

$B_d \to K$ [25], $B_s \to K$ [40] and $B_s \to \phi$ form factors		
$f_0^{B_s}(q^2 = m_\phi^2)$	$f_0^{B_d}(q^2 = m_\phi^2)$	$A_0^{B_s \to \phi}(q^2 = m_K^2)$
0.336 ± 0.023	0.340 ± 0.011	0.426 ± 0.024

Wolfenstein parameters [41]			
A	λ	$\bar{\rho}$	$\bar{\eta}$
$0.8132^{+0.0119}_{-0.0060}$	$0.22500^{+0.00024}_{-0.00022}$	$0.1566^{+0.0085}_{-0.0048}$	$0.3475^{+0.0118}_{-0.0054}$

QCD scale and masses [GeV] [28]							
$\bar{m}_b(\bar{m}_b)$	m_b/m_c	m_{B_d}	m_{B_s}	m_{K^*}	m_ϕ	m_K	Λ_{QCD}
4.18	4.577 ± 0.008	5.27966	5.36692	0.89555	1.01946	0.497611	0.225

SM Wilson Coefficients (at $\mu = 4.18$ GeV)					
$\mathcal{C}_1$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{C}_4$	$\mathcal{C}_5$	$\mathcal{C}_6$
1.082	-0.191	0.014	-0.036	0.009	-0.042
$\mathcal{C}_7/\alpha_{em}$	$\mathcal{C}_8/\alpha_{em}$	$\mathcal{C}_9/\alpha_{em}$	$\mathcal{C}_{10}/\alpha_{em}$	$\mathcal{C}_{7\gamma}^{\text{eff}}$	$\mathcal{C}_{8g}^{\text{eff}}$
-0.011	0.060	-1.254	0.224	-0.318	-0.151

	Relative Error		
Input	$L_{K^*\bar{K}^*}$	$\|P_s\|^2$	$\|P_d\|^2$
f_{K^*}	$(-0.1\%, +0.1\%)$	$(-6.8\%, +7.1\%)$	$(-6.8\%, +7\%)$
$A_0^{B_d}$	$(-22\%, +32\%)$	—	$(-24\%, +28\%)$
$A_0^{B_s}$	$(-28\%, +33\%)$	$(-28\%, +33\%)$	—
λ_{B_d}	$(-0.6\%, +0.2\%)$	$(-4.6\%, +2.1\%)$	$(-4.1\%, +1.9\%)$
$\alpha_2^{K^*}$	$(-0.1\%, +0.1\%)$	$(-3.6\%, +3.7\%)$	$(-3.6\%, +3.6\%)$
X_H	$(-0.2\%, +0.2\%)$	$(-1.8\%, +1.8\%)$	$(-1.6\%, +1.6\%)$
X_A	$(-4.3\%, +4.4\%)$	$(-17\%, +19\%)$	$(-13\%, +14\%)$
κ	$(-1.4\%, +2.2\%)$	—	—
Others	$(-1.3\%, +1.1\%)$	$(-2.7\%, +2.5\%)$	$(-1.6\%, +1.6\%)$

Table 2. Error budget of $L_{K^*\bar{K}^*}$ and $|P_{d,s}|^2$. The relative error of each theoretical input is obtained by varying them individually. The main sources of uncertainty are the form factors, followed by weak annihilation at a significantly smaller level.

	MLR	CDF
$L_{K^*\bar{K}^*}$	$17.2^{+8.3}_{-5.9}$	$19.5^{+9.1}_{-6.7}$
$L_{K\bar{K}}$	$25.5^{+4.0}_{-3.3}$	$26.0^{+3.9}_{-3.6}$
$\hat{L}_{K^*}$	$20.5^{+6.8}_{-6.2}$	$21.3^{+7.2}_{-6.3}$
$\hat{L}_{K}$	$25.3^{+3.7}_{-4.5}$	$25.0^{+4.2}_{-4.1}$
L_{K^*}	$16.6^{+6.9}_{-6.0}$	$17.4^{+6.6}_{-5.8}$
L_{K}	$28.8^{+5.2}_{-4.6}$	$29.2^{+5.5}_{-5.3}$
L_{total}	$23.5^{+3.8}_{-4.0}$	$23.5^{+4.0}_{-3.8}$
R_d	$0.67^{+0.23}_{-0.24}$	$0.70^{+0.30}_{-0.22}$
$\mathcal{B}(B_d \to K^{*0}\bar{K}^{*0}) \times 10^6$	$0.22^{+0.08}_{-0.08}$	$0.23^{+0.10}_{-0.08}$
$\mathcal{B}(B_s \to K^{*0}\bar{K}^{*0}) \times 10^6$	$3.95^{+1.88}_{-1.54}$	$4.36^{+2.23}_{-1.65}$
$\mathcal{B}(B_d \to K^{0}\bar{K}^{0}) \times 10^6$	$1.01^{+0.24}_{-0.16}$	$1.09^{+0.29}_{-0.20}$
$\mathcal{B}(B_s \to K^{0}\bar{K}^{0}) \times 10^6$	$25.6^{+7.5}_{-5.2}$	$28.0^{+8.9}_{-6.2}$

α_i coefficients $\rightarrow a_i$ [BBNS]

$$a_i^p(M_1M_2) = \left(C_i + \frac{C_{i\pm1}}{N_c}\right) N_i(M_2)$$

$$+ \frac{C_{i\pm1}}{N_c}\frac{C_F\alpha_s}{4\pi}\left[V_i(M_2) + \frac{4\pi^2}{N_c} H_i(M_1M_2)\right] + P_i^p(M_2)\,,$$

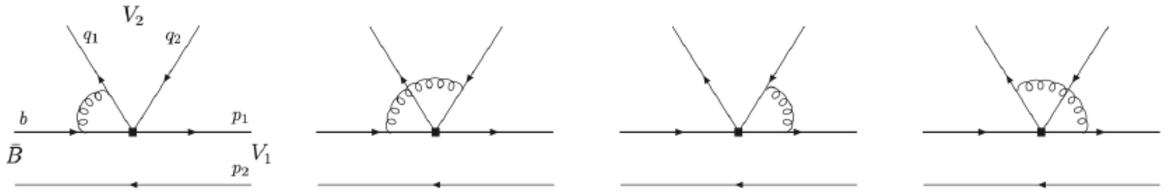


Figure 1: Vertex diagrams.

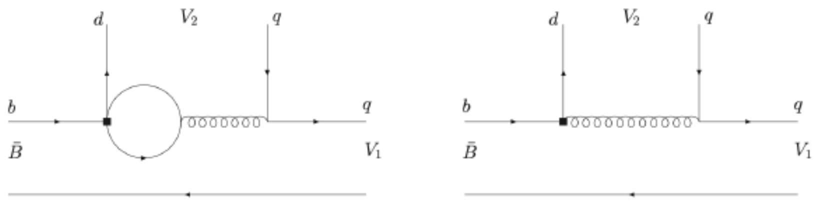


Figure 2: Penguin diagrams.

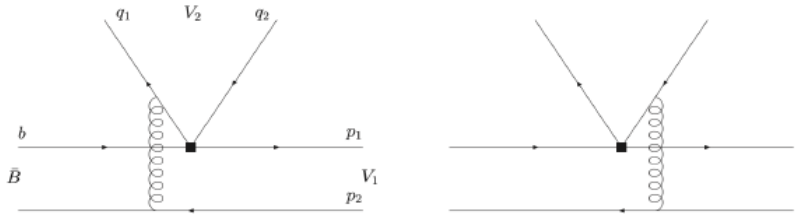


Figure 3: Hard spectator diagrams.

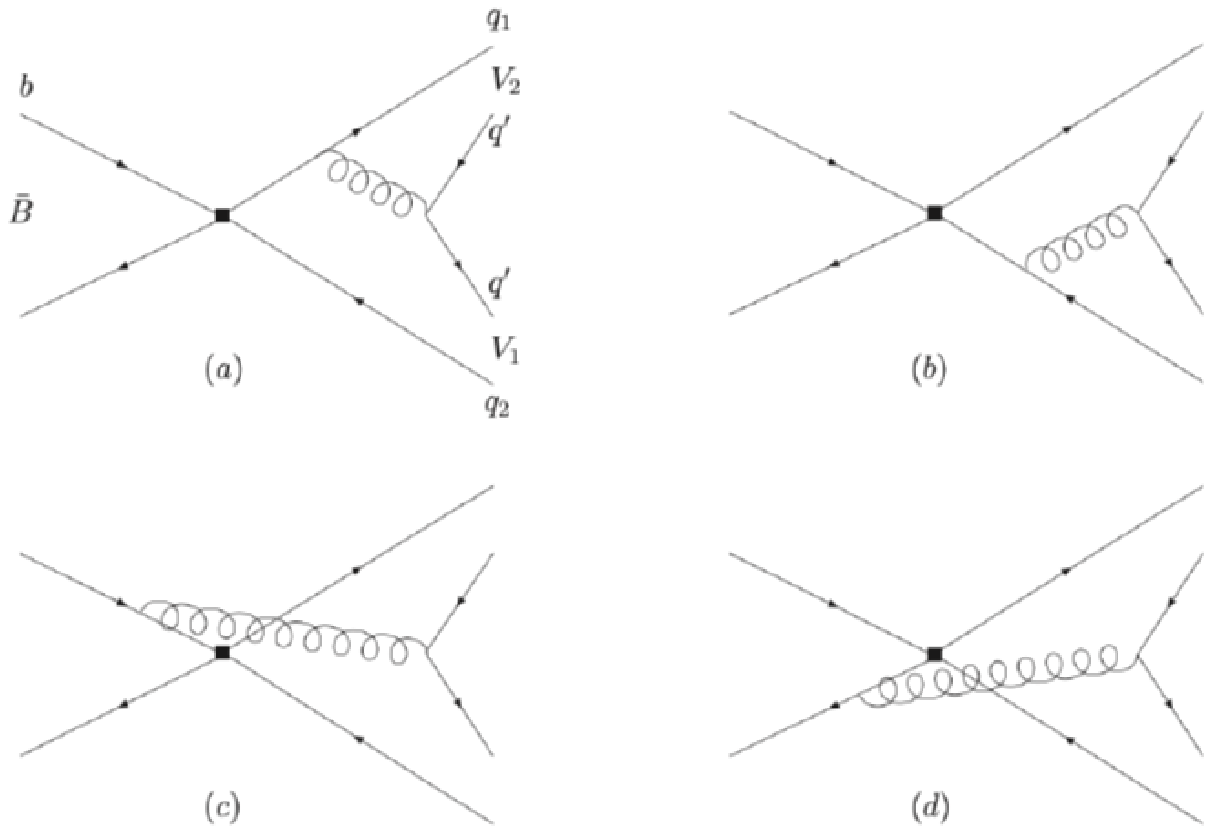


Figure 4: Annihilation diagrams.

Main caveat:

(Existence of some) **Power suppressed** but **IR divergent** spectator scattering and weak annihilation that affects amplitudes: