A new puzzle in nonleptonic B decays

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Based on:

A. Biswas, S. Descotes-Genon, J. Matias and GTX, 2301.10542 [hep-ph]

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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Universität Siegen

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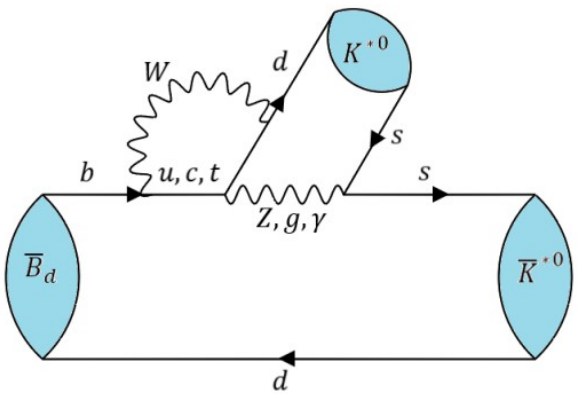
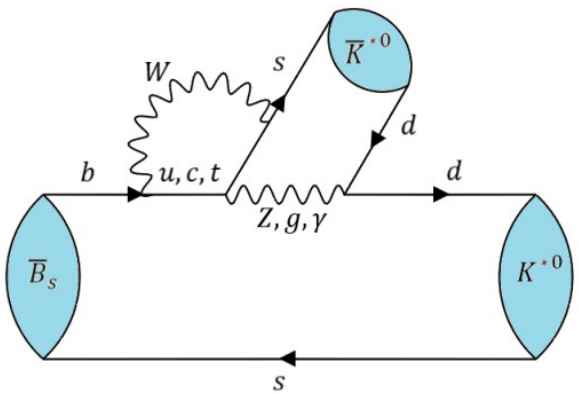
Relevant decay processes

$$\bar{B}_{d,s} \to K^0 \bar{K}^0 \qquad \bar{B}_{d,s} \to K^{*0} \bar{K}^{*0}$$





Penguin mediated decays

$$\bar{A}_f = \lambda_u^{(q)} T_q + \lambda_c^{(q)} P_q = \lambda_u^{(q)} \Delta_q - \lambda_t^{(q)} P_q \qquad \Delta_q = T_q - P_q$$

$$q = d\,,\, s \qquad \lambda_u^{(q)} + \lambda_c^{(q)} + \lambda_t^{(q)} = 0$$

Amplitudes structure

The amplitudes are calculated using QCD Factorization (QCDF)

M. Beneke, M. Neubert
[0308039]

$$T(\bar{B}_d \to \bar{K}^{\,0} K^{\,0}) = A_{\bar{K}\ K}\ [\alpha_4^u - \frac{1}{2}\alpha_{4,EW}^u + \beta_3^u + \beta_4^u - \frac{1}{2}\beta_{3,EW}^u - \frac{1}{2}\beta_{4,EW}^u]$$
$$+A_{K\ \bar{K}}\ [\beta_4^u - \frac{1}{2}\beta_{4,EW}^u]\,,$$
$$P(\bar{B}_d \to \bar{K}^{\,0} K^{\,0}) = A_{\bar{K}\ K}\ [\alpha_4^c - \frac{1}{2}\alpha_{4,EW}^c + \beta_3^c + \beta_4^c - \frac{1}{2}\beta_{3,EW}^c - \frac{1}{2}\beta_{4,EW}^c]$$
$$+A_{K\ \bar{K}}\ [\beta_4^c - \frac{1}{2}\beta_{4,EW}^c]\,,$$

The infrared divergences appearing in *T* and *P* have the same structure

$\Delta_q = T_q - P_q$ is free from infrared divergences

S. Descotes,
J. Matias,
J. Virto
[0603239]

Amplitudes structure

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

Vertex contributions

Amplitudes structure

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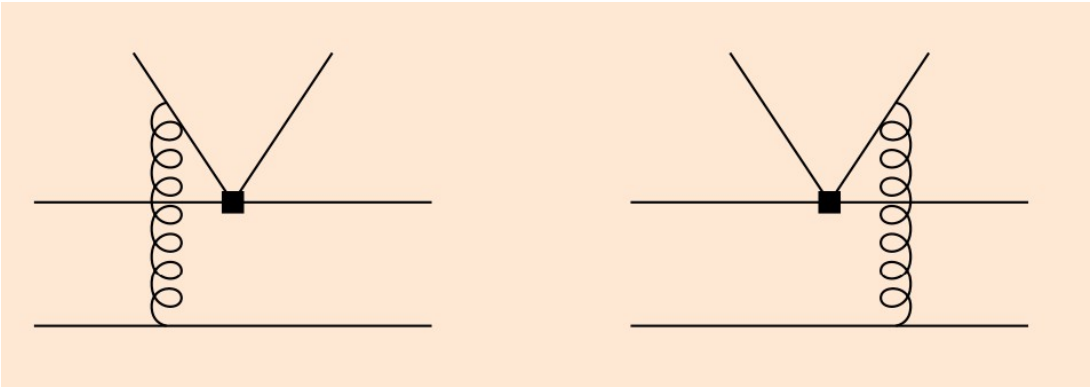
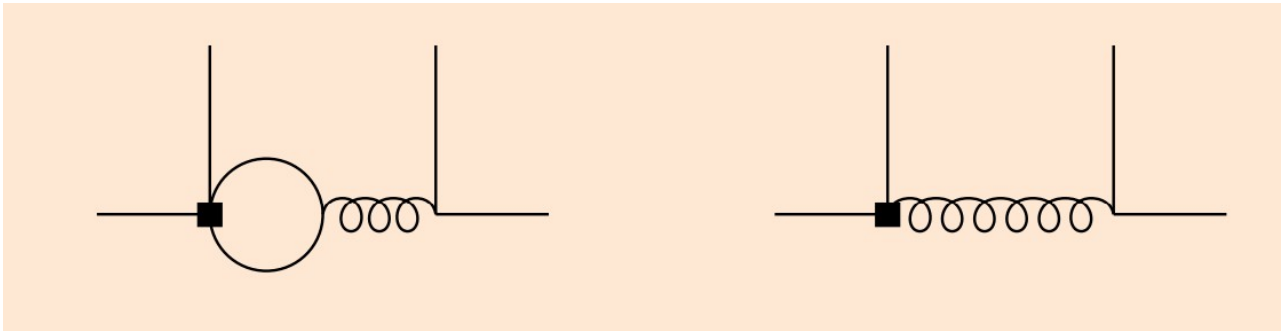
Hard Spectator Scattering



Amplitudes structure

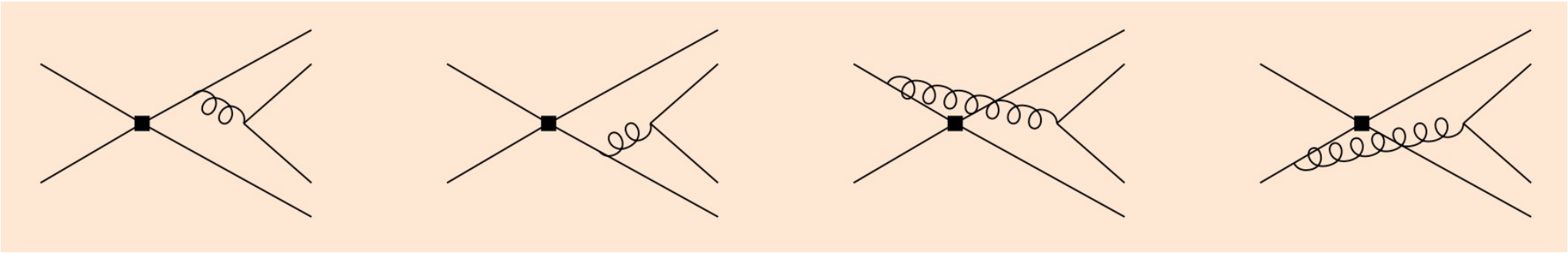
$$a_i^p(M_1M_2) = \left(C_i + \frac{C_{i\pm1}}{N_c}\right) N_i(M_2) + \frac{C_{i\pm1}}{N_c}\frac{C_F\alpha_s}{4\pi}\left[V_i(M_2) + \frac{4\pi^2}{N_c} H_i(M_1M_2)\right] + P_i^p(M_2)$$

Penguin contributions



Amplitudes structure

Annihilation amplitudes β_i



End-point divergences from the integrations of the LCDA $\longrightarrow$ $\int_0^1 \frac{dy}{y} \to X_A^{M_1}$

Optimized Observables

Consider the decays $\bar{B}_{d,s} \to K^{*0}\bar{K}^{*0}$
since the final states are vector states only the longitudinal amplitude is free from infrared divergences at LO.

Construct an optimized observable from the longitudinal amplitude.

Use a ratio involving as initial state *Bs* (numerator) vs *Bd* (denominator) to benefit from *SU(2)*

$$L_{K^*\bar{K}^*} = \rho(m_{K^{*0}}, m_{K^{*0}}) \frac{\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \to K^{*0}\bar{K}^{*0})} \frac{f_L^{B_s}}{f_L^{B_d}} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2}$$

S. Descotes, J. Matias, et al [2011.07867]

$f_L^{B_s}, f_L^{B_d}$ Longitudinal polarization fractions

$\rho(m_{K^{*0}}, m_{K^{*0}})$ Phase space function

Optimized Observables

$$L_{K^*\bar{K}^*} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2} = \kappa \left|\frac{P_s}{P_d}\right|^2 \left[\frac{1 + |\alpha^s|^2 \left|\frac{\Delta_s}{P_s}\right|^2 + 2\mathrm{Re}\left(\frac{\Delta_s}{P_s}\right)\mathrm{Re}(\alpha^s)}{1 + |\alpha^d|^2 \left|\frac{\Delta_d}{P_d}\right|^2 + 2\mathrm{Re}\left(\frac{\Delta_d}{P_d}\right)\mathrm{Re}(\alpha^d)}\right]$$

$$\kappa = \left|\frac{\lambda_u^s + \lambda_c^s}{\lambda_u^s + \lambda_c^s}\right|^2 = 22.91^{+0.48}_{-0.47},$$

$$\alpha^d = \frac{\lambda_u^d}{\lambda_u^d + \lambda_c^d} = -0.0135^{+0.0123}_{-0.0124} + 0.4176^{+0.0123}_{-0.0124} i,$$

$$\alpha^s = \frac{\lambda_u^s}{\lambda_u^s + \lambda_c^s} = 0.0086^{+0.0004}_{-0.0004} - 0.0182^{+0.0006}_{-0.0006} i.$$

S. Descotes, J. Matias, et al [2011.07867]

SU(3)	Naive factorization	QCD factorization
$\left\|\frac{P_s}{P_d}\right\| = 1 \pm 0.3$	$\left\|\frac{P_s}{P_d}\right\| = 0.91^{+0.20}_{-0.17}$	$\left\|\frac{P_s}{P_d}\right\| = 0.92^{+0.20}_{-0.18}$

Theoretical and Experimental values

The following result is reported by LHCb at $3\ fb^{-1}$

$$\frac{\mathcal{B}_{B_d \to K^{*0}\bar{K}^{*0}}}{\mathcal{B}_{B_s \to K^{*0}\bar{K}^{*0}}} = 0.0758 \pm 0.0057(\text{stat}) \pm 0.0025(\text{syst}) \pm 0.0016 \left(\frac{f_s}{f_d}\right)$$

LHCb [1905.06662, 0708.2248]

The polarization fractions have been measured to be

$$f_L(B_d \to K^{0*}K^{0*}) = 0.73 \pm 0.05$$

$$f_L(\bar{B}_s \to K^{0*}\bar{K}^{0*}) = 0.240 \pm 0.040$$

LHCb [1905.06662], BABAR [0708.2248]

S. Descotes, J. Matias, et al [2011.07867]

LHCb [1503.05362]

Final Experimental result

$$L^{\text{exp}}_{K^*\bar{K}^*} = 4.43 \pm 0.92$$

Theoretical and Experimental values

Final Experimental result

$$L^{\rm exp}_{K^*\bar{K}^*} = 4.43 \pm 0.92$$

Theory

SU(3)

$$L_{K^*\bar{K}^*} = 23^{+16}_{-12} \qquad 1.9\sigma$$

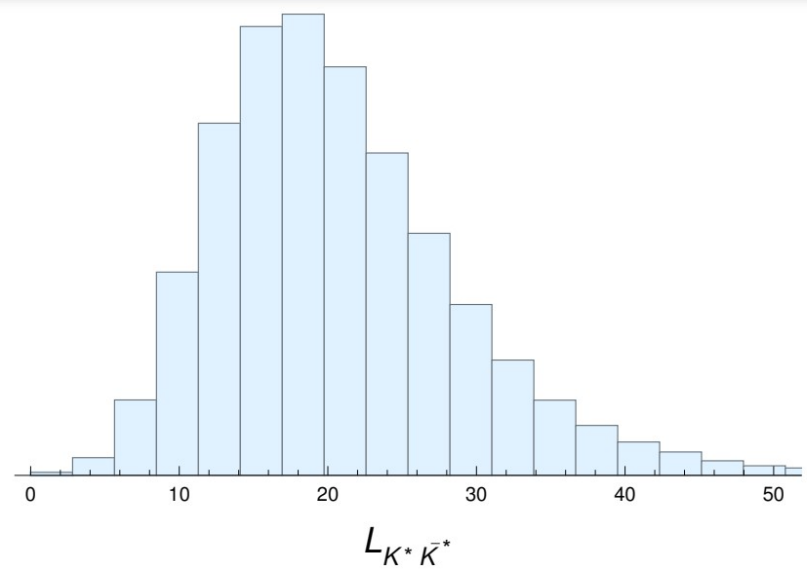
Naive factorization

$$L_{K^*\bar{K}^*} = 19.2^{+9.3}_{-6.5} \qquad 3.0\sigma$$

QCD factorization

$$L^{\rm SM}_{K^*\bar{K}^*} = 19.53^{+9.14}_{-6.64} \qquad 2.6\sigma$$

Montecarlo distribution obtained from varying the nuisance parameters



2.6 σ discrepancy between theory and experiment

Alternative Observables

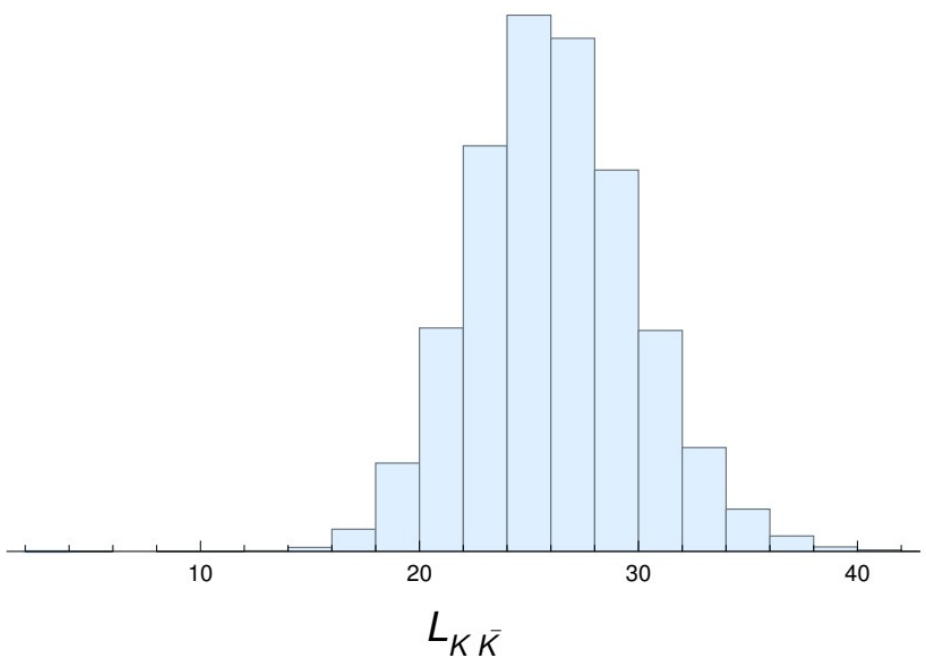
Proceed in an analogous way to define

$$L_{K\bar{K}} = \rho(m_{K^0}, m_{K^0}) \frac{\mathcal{B}(\bar{B}_s \to K^0 \bar{K}^0)}{\mathcal{B}(\bar{B}_d \to K^0 \bar{K}^0)} = \frac{|A^s|^2 + |\bar{A}^s|^2}{|A^d|^2 + |\bar{A}^d|^2},$$

Experimental result $L^{\rm exp}_{K\bar{K}} = 14.58 \pm 3.37$

QCD factorization $L^{\rm SM}_{K\bar{K}} = 26.00^{+3.88}_{-3.59}$

2.4 σ discrepancy



Explaining the tensions via NP

Effective theory description

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{p=c,u} \lambda_p^{(q)} \left(\mathcal{C}_{1s}^p Q_{1s}^p + \mathcal{C}_{2s}^p Q_{2s}^p + \sum_{i=3\ldots10} \mathcal{C}_{is} Q_{is} + \mathcal{C}_{7\gamma s} Q_{7\gamma s} + \mathcal{C}_{8gs} Q_{8gs} \right)$$

$$Q_{1s}^p = (\bar{p}b)_{V-A}(\bar{s}p)_{V-A}\,,$$

$$Q_{2s}^p = (\bar{p}_i b_j)_{V-A}(\bar{s}_j p_i)_{V-A}\,,$$

$$Q_{3s} = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V-A}\,,$$

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

$$Q_{5s} = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V+A}\,,$$

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

$$Q_{7s} = (\bar{s}b)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}q)_{V+A}\,,$$

$$Q_{8s} = (\bar{s}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V+A}\,,$$

$$Q_{9s} = (\bar{s}b)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}q)_{V-A}\,,$$

$$Q_{10s} = (\bar{s}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V-A}\,,$$

$$Q_{7\gamma s} = \frac{-e}{8\pi^2}\, m_b \bar{s}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu} b\,,$$

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

Potential NP in $b \to s\, q\, \bar{q}$ and $b \to s\,(g\,\gamma)$ transitions?.

Explaining the tensions via NP

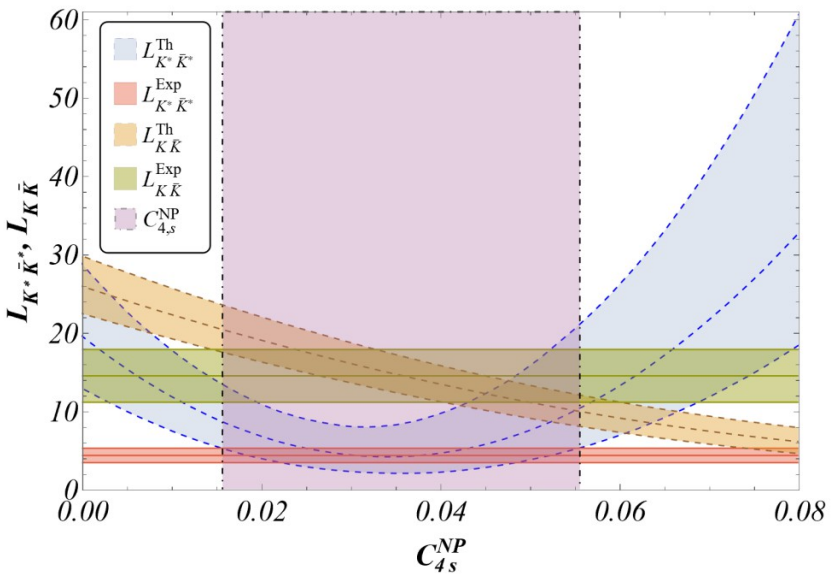
Test NP contributions in different Wilson coefficients, the best solutions are given in terms of C_{4s}^{NP}, C_{6s}^{NP} and C_{8gs}^{NP}

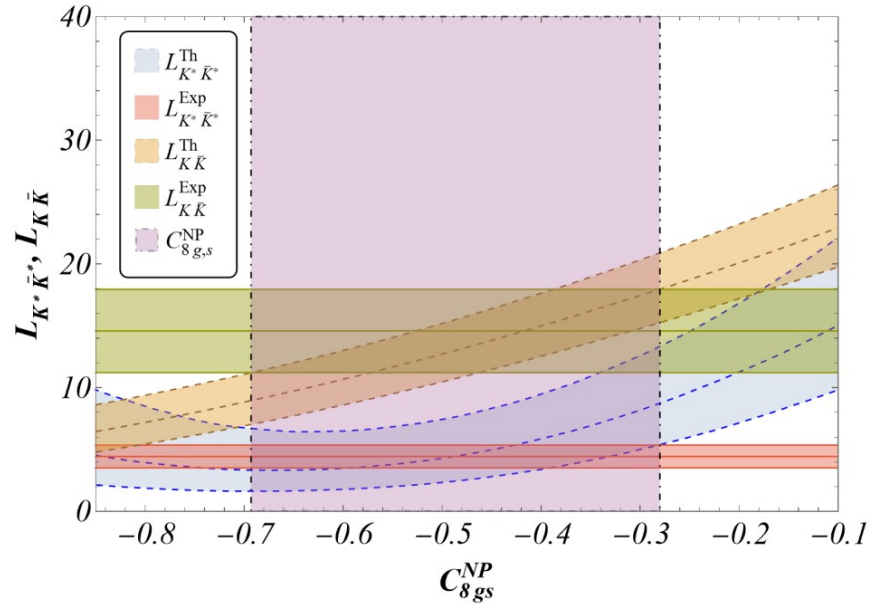
$$L_{K^*\bar{K}^*} = 19.25 - 936.23\, \mathcal{C}_{4s}^{\rm NP} + 14383.60\, (\mathcal{C}_{4s}^{\rm NP})^2 + 55.44\, \mathcal{C}_{6s}^{\rm NP} + 73.70\, (\mathcal{C}_{6s}^{\rm NP})^2 + 50.53\, \mathcal{C}_{8gs}^{\rm NP} + 39.38\, (\mathcal{C}_{8gs}^{\rm NP})^2 - 711.45\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{6s}^{\rm NP} - 1502.07\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP} + 43.76\, \mathcal{C}_{6s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP}$$

$$L_{K\bar{K}} = 25.90 - 380.76\, \mathcal{C}_{4s}^{\rm NP} + 1646.11\, (\mathcal{C}_{4s}^{\rm NP})^2 - 631.58\, \mathcal{C}_{6s}^{\rm NP} + 4313.58\, (\mathcal{C}_{6s}^{\rm NP})^2 + 31.92\, \mathcal{C}_{8gs}^{\rm NP} + 10.38\, (\mathcal{C}_{8gs}^{\rm NP})^2 + 5318.62\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{6s}^{\rm NP} - 257.90\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP} - 421.08\, \mathcal{C}_{6s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP}$$

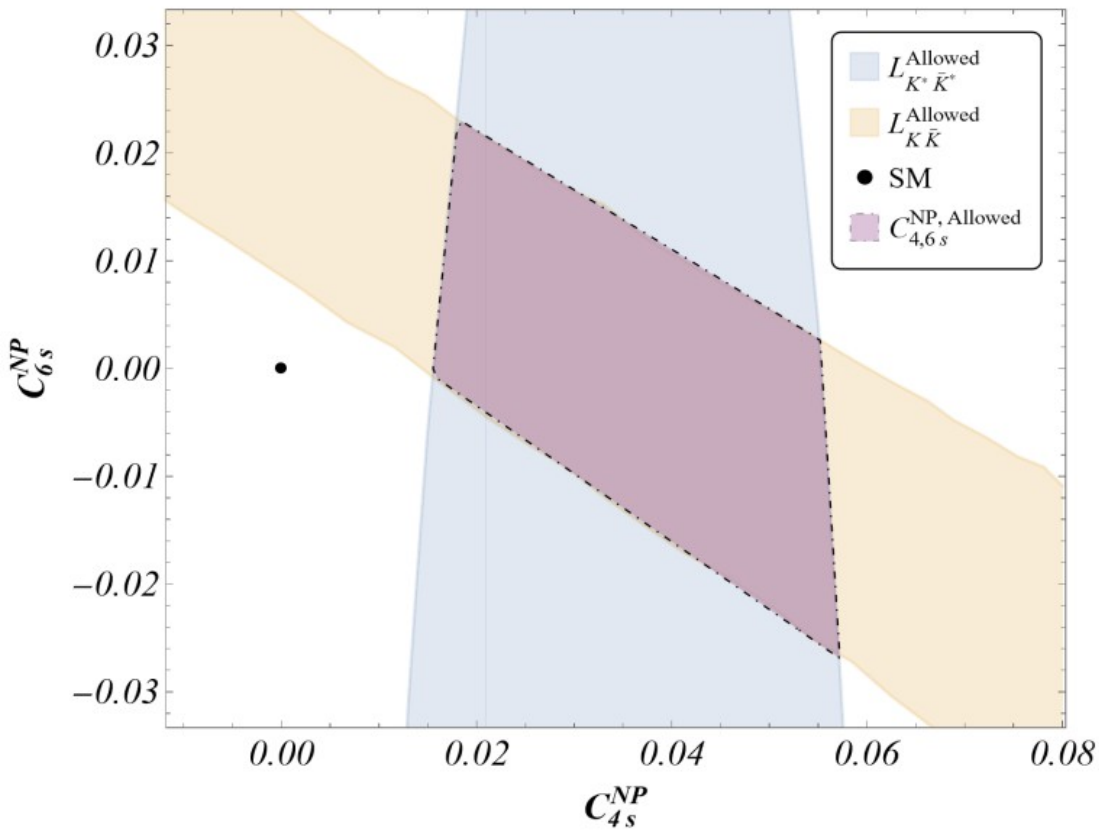
Explaining the tensions via NP

Solutions for C_{4s}^{NP} and C_{8gs}^{NP} independently exist





Explaining the tensions via NP



Solutions for C_{4s}^{NP} and C_{6s}^{NP} combined

Notice that C_{6s}^{NP} requires $C_{4s}^{NP} \neq 0$

Individual Branching Fractions

$B \to V\,V$

Longitudinal $\mathcal{B}(\bar{B}_d \to K^{*0}\bar{K}^{*0})$ $[10^{-7}]$	
SM (QCDF)	Experiment
$2.27^{+0.98}_{-0.74}$	$6.04^{+1.81}_{-1.78}$

$1.8\,\sigma$

Longitudinal $\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^{*0})$ $[10^{-6}]$	
SM (QCDF)	Experiment
$4.36^{+2.23}_{-1.65}$	$2.62^{+0.85}_{-0.75}$

$0.9\,\sigma$

$B \to P\,P$

$\mathcal{B}(\bar{B}_d \to K^0\bar{K}^0)$ $[10^{-6}]$	
SM (QCDF)	Experiment
$1.09^{+0.29}_{-0.20}$	1.21 ± 0.16

$0.4\,\sigma$

$\mathcal{B}(\bar{B}_s \to K^0\bar{K}^0)$ $[10^{-5}]$	
SM (QCDF)	Experiment
$2.80^{+0.89}_{-0.62}$	1.76 ± 0.33

$1.6\,\sigma$

Individual Branching Fractions

$B \to V\,V$

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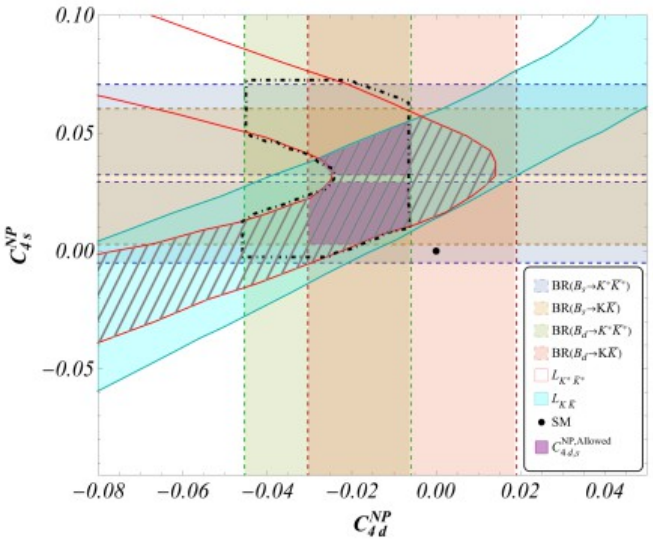
$\mathcal{B}(\bar{B}_d \to K^0\bar{K}^0)$ $[10^{-6}]$	
SM (QCDF)	Experiment
$1.09^{+0.29}_{-0.20}$	1.21 ± 0.16

$0.4\,\sigma$

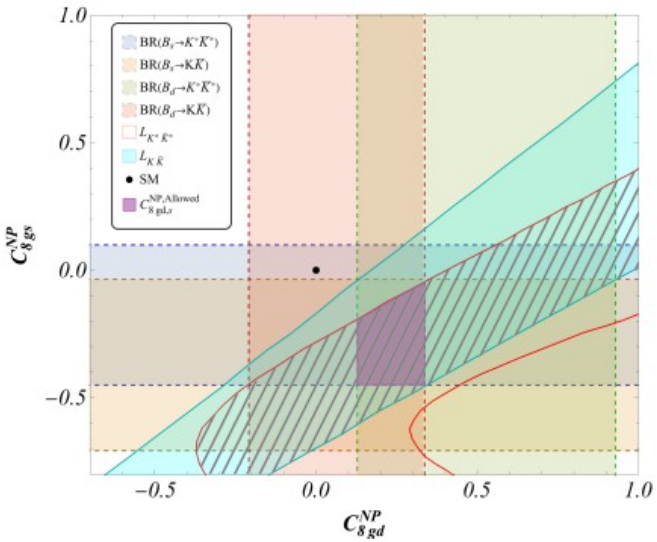
$\mathcal{B}(\bar{B}_s \to K^0\bar{K}^0)$ $[10^{-5}]$	
SM (QCDF)	Experiment
$2.80^{+0.89}_{-0.62}$	1.76 ± 0.33

$1.6\,\sigma$

NP Explanations for all the observables



Magenta: NP region with $C^{NP}_{6d\,,6s}=0$



Magenta: NP explanation of all the observables

Dotted black region: $C^{NP}_{6d\,,6s}$ are allowed to float freely

Falsifying the different NP explanations

We propose extra observables that can help to identify potential NP effects constructed out of the transitions $B \to P\,V$ and $B \to V\,P$

$$\hat{L}_{K^*} = \rho(m_{K^0}, m_{K^{*0}}) \frac{\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^0)}{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}K^0)} = \frac{|A^s|^2 + |\bar{A}^s|^2}{|A^d|^2 + |\bar{A}^d|^2}$$

$$\hat{L}_{K^*}^{\rm SM} = 21.30^{+7.19}_{-6.30}$$

$$\hat{L}_{K} = \rho(m_{K^0}, m_{K^{*0}}) \frac{\mathcal{B}(\bar{B}_s \to K^{0}\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \to \bar{K}^{0}K^{*0})} = \frac{|A^s|^2 + |\bar{A}^s|^2}{|A^d|^2 + |\bar{A}^d|^2}$$

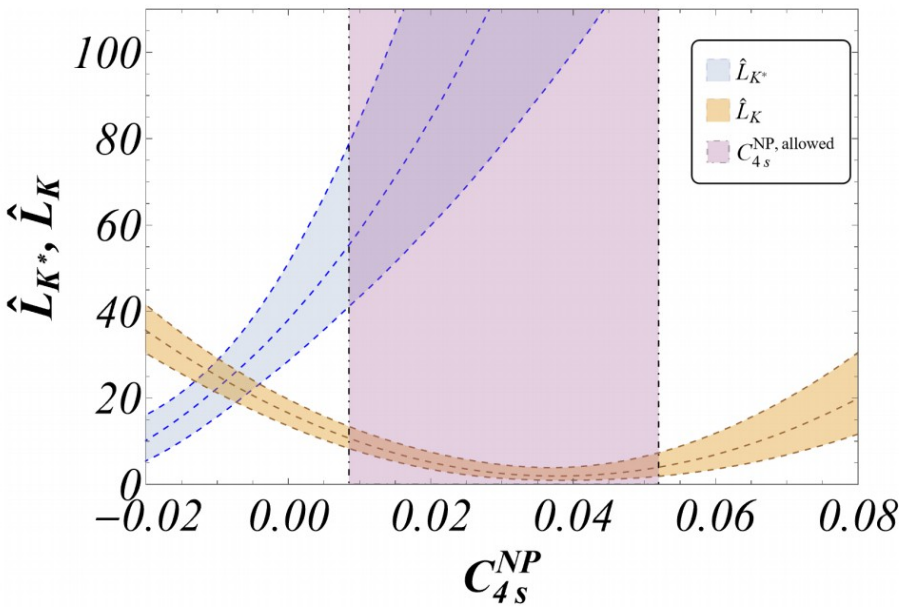
$$\hat{L}_{K}^{\rm SM} = 25.01^{+4.21}_{-4.07}$$

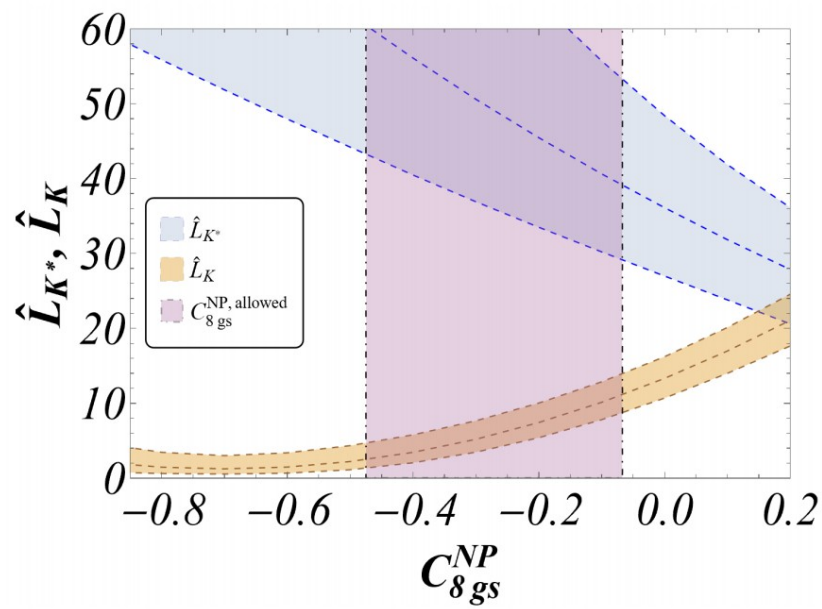
$$\begin{aligned}\hat{L}_{K^*} = {} & 21.00 + 1040.25\, \mathcal{C}_{4s}^{\rm NP} + 12886.60\, (\mathcal{C}_{4s}^{\rm NP})^2 - 1504.72\, \mathcal{C}_{6s}^{\rm NP} + 27037.90\, (\mathcal{C}_{6s}^{\rm NP})^2 \\ & - 26.72\, \mathcal{C}_{8gs}^{\rm NP} + 8.52\, (\mathcal{C}_{8gs}^{\rm NP})^2 - 37304.70\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{6s}^{\rm NP} - 662.39\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP} \\ & + 959.60\, \mathcal{C}_{6s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP}\,,\end{aligned}$$

$$\begin{aligned}\hat{L}_{K} = {} & 25.04 - 1201.22\, \mathcal{C}_{4s}^{\rm NP} + 15994.20\, (\mathcal{C}_{4s}^{\rm NP})^2 + 149.47\, \mathcal{C}_{6s}^{\rm NP} + 240.53\, (\mathcal{C}_{6s}^{\rm NP})^2 \\ & + 66.04\, \mathcal{C}_{8gs}^{\rm NP} + 46.59\, (\mathcal{C}_{8gs}^{\rm NP})^2 - 3252.68\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{6s}^{\rm NP} - 1723.21\, \mathcal{C}_{4s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP} \\ & + 182.57\, \mathcal{C}_{6s}^{\rm NP}\, \mathcal{C}_{8gs}^{\rm NP}\,.\end{aligned}$$

Falsifying the different NP explanations

Predictions from Possible New Physics scenarios





$$C_{4\mathrm{d}}^{NP} = -0.01$$

$$C_{8\mathrm{gd}}^{NP} = 0.3$$

In this scenario $\hat{L}_{K^*}$ is enhanced by a factor of 3 - 5.

Falsifying the different NP explanations

Since B meson tagging is particularly challenging we define the alternative observables

$$L_{K^*} = 2\,\rho(m_{K^0}, m_{K^{*0}}) \frac{\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^0)}{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}K^0) + \mathcal{B}(\bar{B}_d \to \bar{K}^0 K^{*0})} = \frac{2R_d}{1+R_d}\hat{L}_{K^*}$$

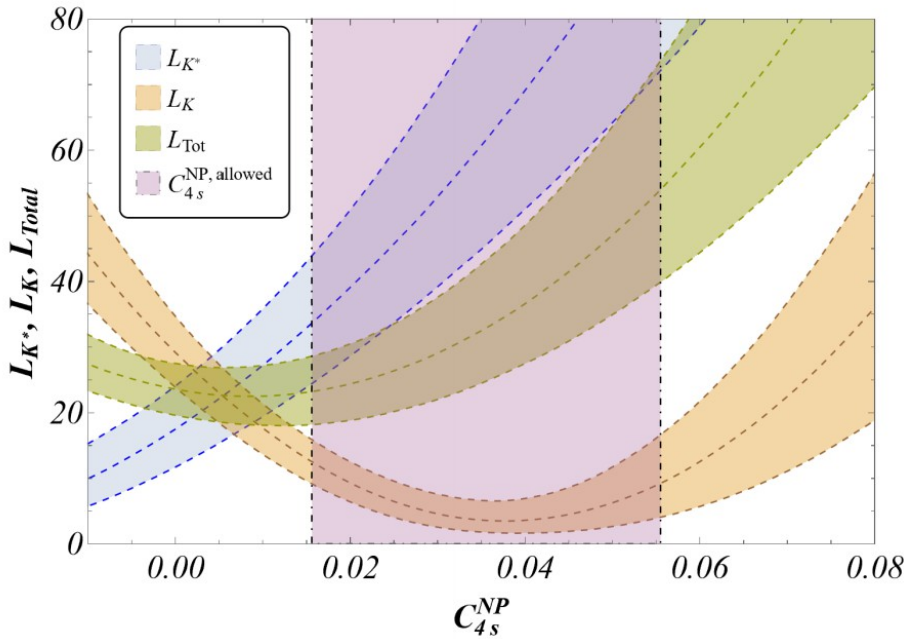
$$L_K = 2\,\rho(m_{K^0}, m_{K^{*0}}) \frac{\mathcal{B}(\bar{B}_s \to K^{0}\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}K^0) + \mathcal{B}(\bar{B}_d \to \bar{K}^0 K^{*0})} = \frac{2}{1+R_d}\hat{L}_{K}$$

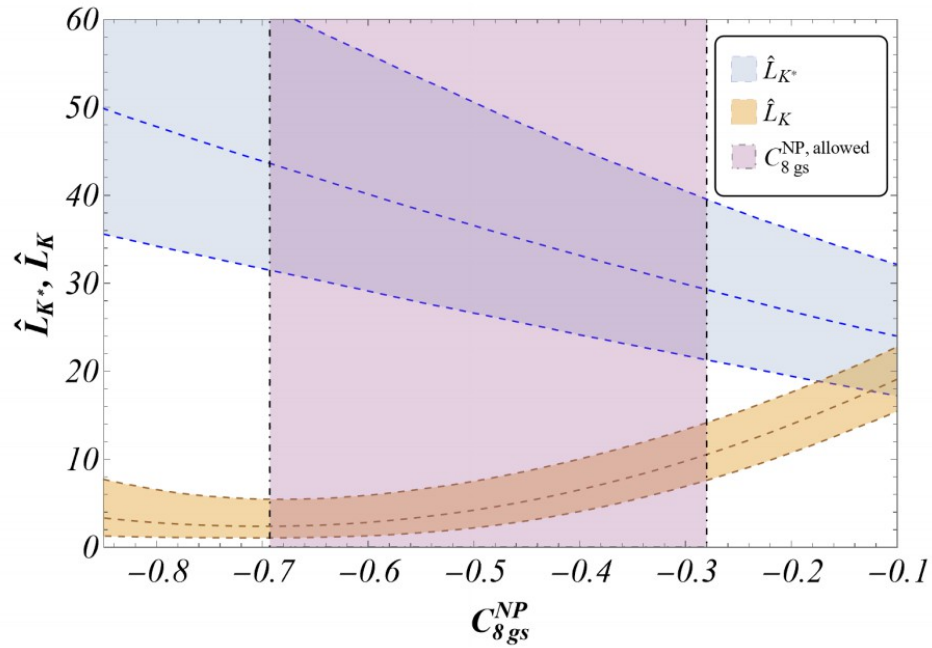
$$\begin{aligned} L_{\text{total}} &= \rho(m_{K^0}, m_{K^{*0}}) \left(\frac{\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^0) + \mathcal{B}(\bar{B}_s \to K^{0}\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}K^0) + \mathcal{B}(\bar{B}_d \to \bar{K}^0 K^{*0})} \right) \\ &= \frac{L_{K^*} + L_K}{2} = \frac{\hat{L}_K + \hat{L}_{K^*} R^d}{1+R^d} \end{aligned}$$

$$R^d = \frac{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}K^0)}{\mathcal{B}(\bar{B}_d \to \bar{K}^0 K^{*0})}$$

$L_K^{\text{SM}} = 29.16^{+5.49}_{-5.25}$ $L_{K^*}^{\text{SM}} = 17.44^{+6.59}_{-5.82}$ $L_{\text{total}}^{\text{SM}} = 23.48^{+3.95}_{-3.82}$ $R^{d\,\text{SM}} = 0.70^{+0.30}_{-0.22}$

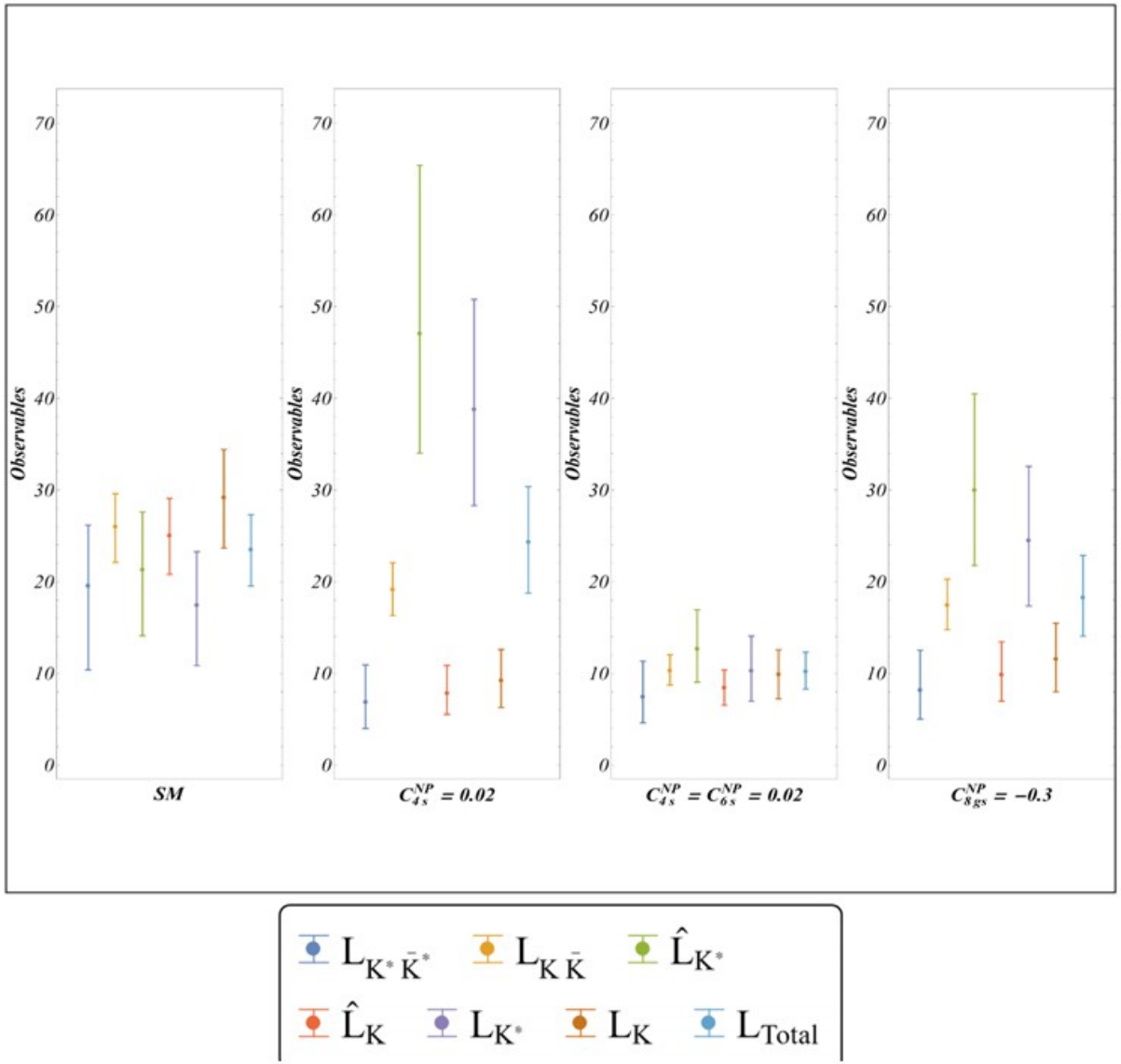
Falsifying the different NP explanations





The sensitivity towards NP in this observables is reduced with respect to the ones where tagging was present

Falsifying the different NP explanations



Deviation patterns

Conclusions

- There are interesting deviation patterns in the non-leptonic decays

$$\bar{B}_{d,s} \to K^0 \bar{K}^0 \quad \text{and} \quad \bar{B}_{d,s} \to K^{*0} \bar{K}^{*0} \ .$$

- There is a tension between theory and experiment in the optimized observables $L_{K^* \overline{K^*}}$ and $L_{K \overline{K}}$ at the level of $2.6\,\sigma$ and $2.4\,\sigma$ respectively.

- The deviations can also be found in the individual branching fractions.

- The tension between theory and experiment can be explained if New Physics is assumed in combinations of the Wilson coefficients

$$C^{NP}_{4s} \ , \ C^{NP}_{6s} \ , \ C^{NP}_{8gs} \quad \Big| \quad C^{NP}_{4d} \ , \ C^{NP}_{6d} \ , \ C^{NP}_{8gd}$$

- Further observables based on the decays $B \to K^0 \overline{K^{*0}}$ can be constructed to test and falsify different New Physics scenarios .

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