Optimized Observables in non-leptonic decays

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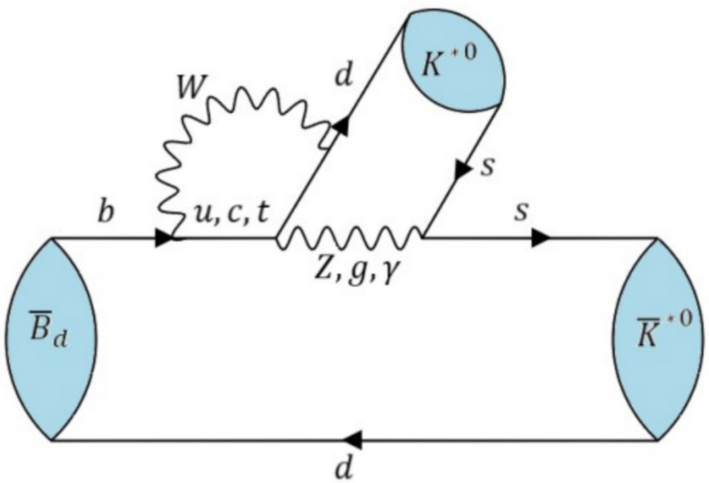
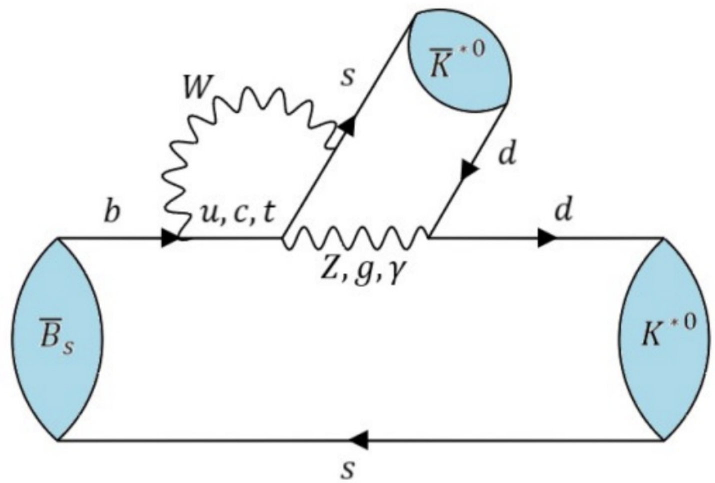
Relevant decay processes





Penguin induced processes: b → d and b → s

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

$$\lambda_u^{(q)} + \lambda_c^{(q)} + \lambda_t^{(q)} = 0$$

Free from infrared divergences $\quad \Delta_q = T_q - P_q$

Amplitude structure

The amplitudes are calculated using QCDF

Beneke et. al. 0308039 [hep-ph]

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

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

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

$$\alpha_4^p(M_1 M_2) = a_4^p(M_1 M_2) + r_\chi^{M_2}\, a_6^p(M_1 M_2)$$

Amplitude structure

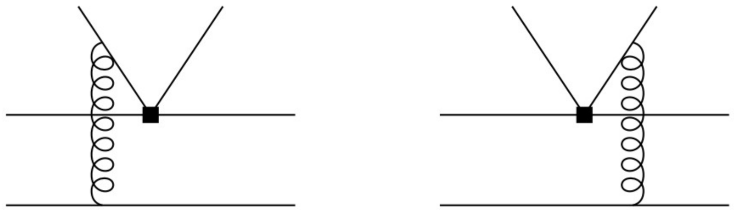
$$a_i^p(M_1 M_2) = \left(C_i + \frac{C_{i\pm1}}{N_c}\right) N_i(M_2) + \frac{C_{i\pm1}}{N_c}\,\frac{C_F\alpha_s}{4\pi}\left[V_i(M_2) + \frac{4\pi^2}{N_c}H_i(M_1M_2)\right] + P_i^p(M_2)\,,$$

Vertex corrections

Amplitude structure

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

Spectator scattering



Amplitude structure

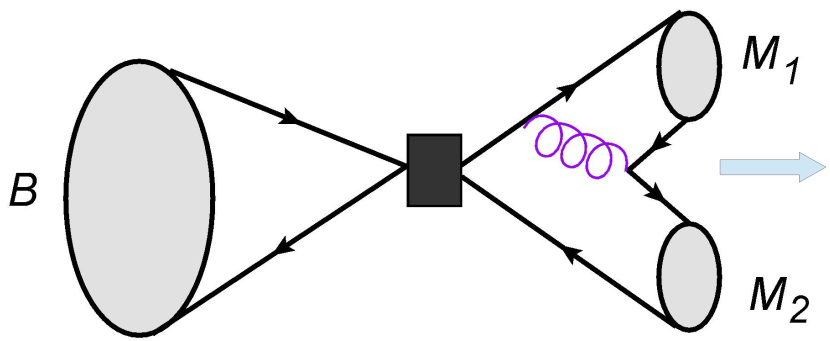
$$a_i^p(M_1M_2) = \left(C_i + \frac{C_{i\pm1}}{N_c}\right) N_i(M_2) + \frac{C_{i\pm1}}{N_c}\frac{C_F\alpha_s}{4\pi}\left[V_i(M_2) + \frac{4\pi^2}{N_c}H_i(M_1M_2)\right] + P_i^p(M_2),$$

Penguin contributions

Annihilation contributions

Weak annihilation topolgies are affected by LCDA end point singularities

$$\int_0^1 \frac{dy}{y} \to X_A$$



β, b

Educated Ansatz

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

$$0 \le \rho_A \le 1, \quad 0 \le \varphi_A \le 2\pi$$

Data can be used to get bounds for these contributuions

GTX, T. Huber 2111.06418 [hep-ph]

For decays of *B* mesons into pseudoscalar-pseudoscalar final states

$$|\beta_i| \le 0.40 \quad \text{for} \quad |\alpha_1| \approx 1$$

SU(3) flavour exact

Another possibility is to construct observables with low sensitivity to these contributions

Optimized Observables

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

U-spin related channels

Optimized Observables

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

↑ Phase space factor

Optimized Observables

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

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

S. Descotes, J. Matias, et al 2011.07867 [hep-ph]

Only the longitudinal component is factorizable (vector-vector final states)

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

$$\begin{aligned} \alpha^d &= (-0.0136^{+0.0095}_{-0.0096}) + i(0.4181^{+0.0085}_{-0.0064}), \\ \alpha^s &= (0.00863^{+0.00040}_{-0.00036}) + i(-0.01829^{+0.00037}_{-0.00042}), \\ \kappa &= \left|\frac{\lambda_c^s + \lambda_u^s}{\lambda_c^d + \lambda_u^d}\right|^2 = 22.92^{+0.52}_{-0.30}. \end{aligned}$$

SU(3) $\left|\frac{P_s}{P_d}\right| = 1 \pm 0.3$

Naive Factorization $\left|\frac{P_s}{P_d}\right| = 0.91^{+0.20}_{-0.17}$

QCD Factorization $\left|\frac{P_s}{P_d}\right| = 0.92^{+0.20}_{-0.18}$

Optimized Observables

Under the assumption of *U-Spin symmetry* in the sources of infrared divergences we expect that they fluctuate in the same direction in numerator and denominator

Theory prediction

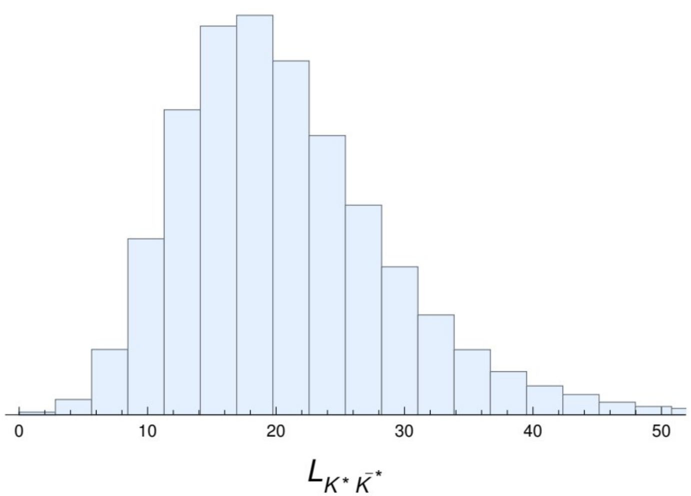
$$\text{naive } SU(3) : L_{K^*\bar{K}^*} = 23^{+16}_{-12} \qquad 1.9\sigma\,,$$

$$\text{fact } SU(3) : L_{K^*\bar{K}^*} = 19.2^{+9.3}_{-6.5} \qquad 3.0\sigma\,,$$

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

S. Descotes, J. Matias, et al
2011.07867 [hep-ph]

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



Optimized Observables

Experimental measurement

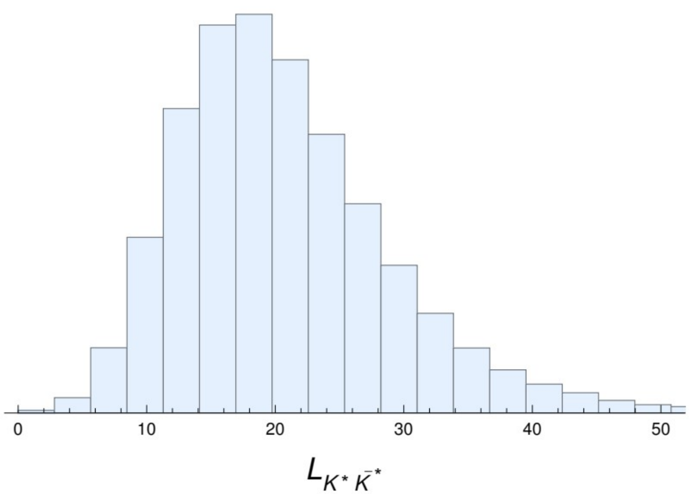
$$\frac{\mathcal{B}_{B_d\to K^{*0}\bar{K}^{*0}}}{\mathcal{B}_{B_s\to K^{*0}\bar{K}^{*0}}} = 0.0758 \pm 0.0057(\text{stat}) \pm 0.0025(\text{syst}) \pm 0.0016 \left(\frac{f_s}{f_d}\right)$$

LHCb [1905.06662, 0708.2248]

Measured longitudinal polarisation fractions	
$f_L(\bar{B}_d \to K^{0*}\bar{K}^{0*})$	$f_L(\bar{B}_s \to K^{0*}\bar{K}^{0*})$
0.73 ± 0.05	0.240 ± 0.040

LHCb [1905.06662], BABAR [0708.2248]
S. Descotes, J. Matias, et al 2011.07867 [hep-ph]

LHCb [1503.05362]



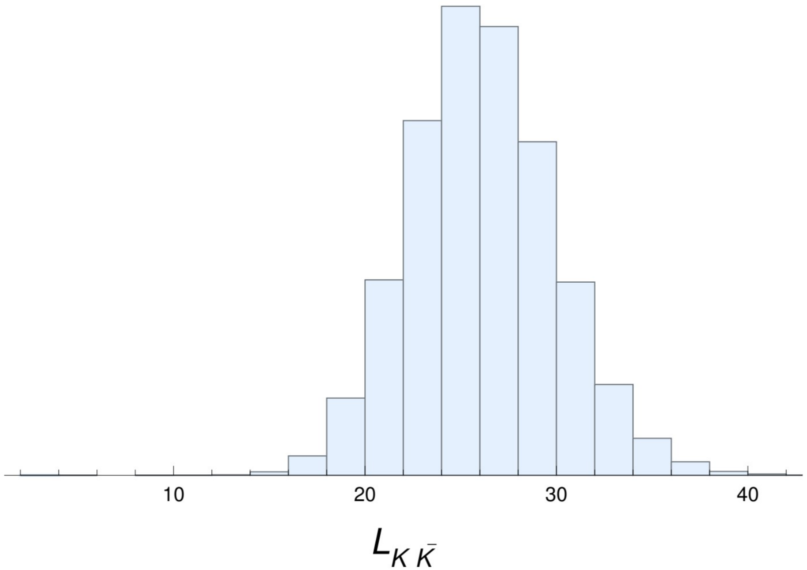
$$L^{\text{exp}}_{K^*\bar{K}^*} = 4.43 \pm 0.92$$

$2.6\ \sigma$ tension

Optimized Observables

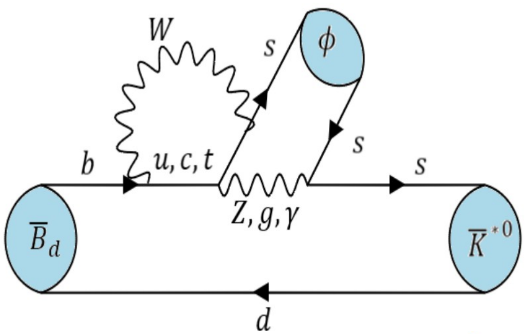
$$L_{K\bar{K}} = \rho(m_{K^0}, m_{K^0}) \frac{\mathcal{B}(\bar{B}_s \to K^0\bar{K}^0)}{\mathcal{B}(\bar{B}_d \to K^0\bar{K}^0)} = \frac{|A^s|^2 + |\bar{A}^s|^2}{|A^d|^2 + |\bar{A}^d|^2}$$

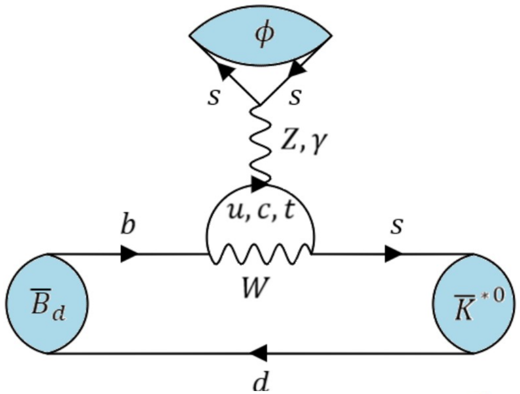
$L_{K\bar{K}}^{\mathrm{SM}} = 26.00^{+3.88}_{-3.59}$ $\quad L_{K\bar{K}}^{\mathrm{exp}} = 14.58 \pm 3.37$ $\quad 2.4\ \sigma$ tension



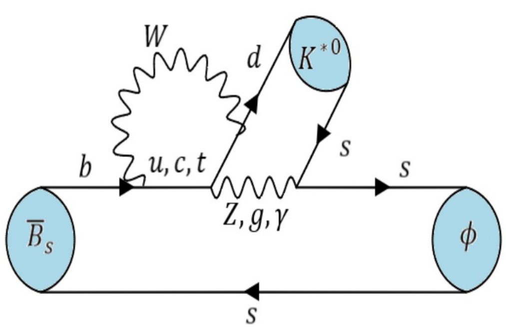
Optimized Observables

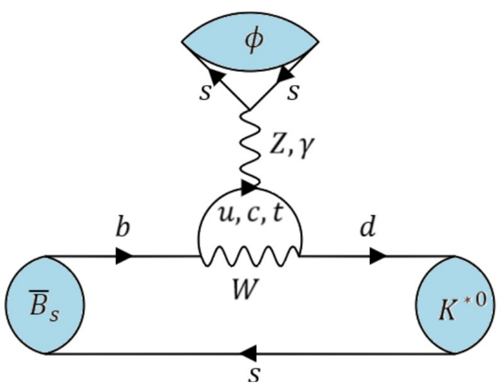
$B_{d(s)} \to K^{(*)0}\phi$ processes





$$A(\bar{B}_d \to \bar{K}^{*0}\phi) = \sum_{p=u,c} \lambda_p^{(s)} \left(a_4^p + a_3 + a_5 - \frac{1}{2}(a_7^p + a_9^p + a_{10}^p) \right) A_{K^*\phi}$$
$$+ \left(\lambda_u^{(s)} + \lambda_c^{(s)}\right) \left(b_3 - \frac{1}{3} b_3^{\rm EW}\right) B_{K^*\phi}$$

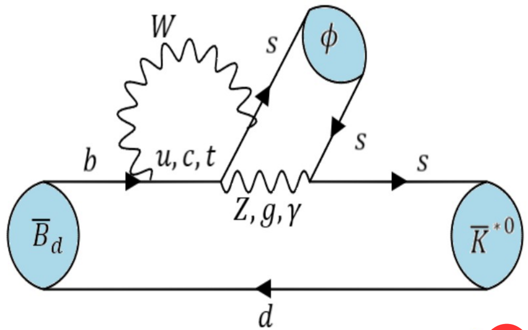


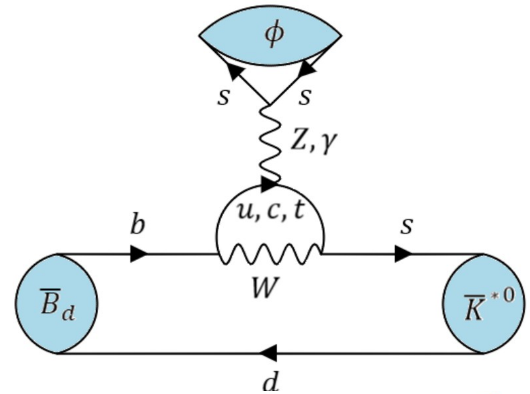


$$A(\bar{B}_s \to K^{*0}\phi) = \sum_{p=u,c} \lambda_p^{(d)} \left[\left(a_4^p - \frac{1}{2} a_{10}^p \right) A_{\phi K^*} + \left(a_3 + a_5 - \frac{1}{2}(a_7^p + a_9^p) \right) A_{K^*\phi} \right]$$
$$+ \left(\lambda_u^{(d)} + \lambda_c^{(d)}\right) \left(b_3 - \frac{1}{3} b_3^{\rm EW}\right) B_{K^*\phi},$$

Optimized Observables

$B_{d(s)} \to K^{(*)0}\phi$ processes

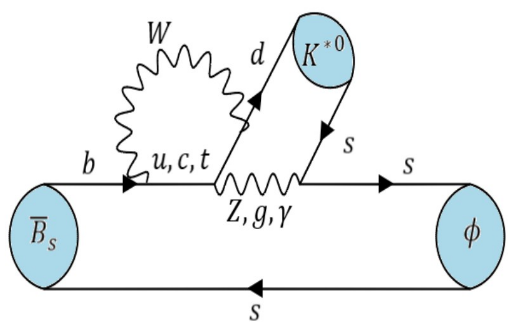


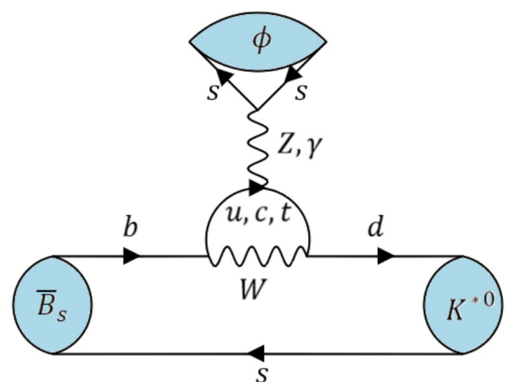


$$A(\bar{B}_d \to \bar{K}^{*0}\phi) = \sum_{p=u,c} \lambda_p^{(s)} \left(a_4^p + a_3 + a_5 - \frac{1}{2}(a_7^p + a_9^p + a_{10}^p) \right) A_{K^*\phi}$$
$$+ \left(\lambda_u^{(s)} + \lambda_c^{(s)}\right)\left(b_3 - \frac{1}{3} b_3^{\rm EW}\right) B_{K^*\phi}$$

Penguin dominance

p=c





$$A(\bar{B}_s \to K^{*0}\phi) = \sum_{p=u,c} \lambda_p^{(d)} \left[\left(a_4^p - \frac{1}{2} a_{10}^p \right) A_{\phi K^*} + \left(a_3 + a_5 - \frac{1}{2}(a_7^p + a_9^p) \right) A_{K^*\phi} \right]$$
$$+ \left(\lambda_u^{(d)} + \lambda_c^{(d)}\right)\left(b_3 - \frac{1}{3} b_3^{\rm EW}\right) B_{K^*\phi},$$

Optimized Observables

$$L_{K^*\phi} = \rho(m_{K^{*0}}, m_\phi) \frac{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}\phi)}{\mathcal{B}(\bar{B}_s \to K^{*0}\phi)} \frac{f_L^{B_d}}{f_L^{B_s}}$$

Measured longitudinal polarisation fractions	
$f_L(\bar{B}_d \to \bar{K}^{0*}\phi)$	$f_L(\bar{B}_s \to K^{0*}\phi)$
0.497 ± 0.017	0.51 ± 0.17

BABAR 0808.3586, BELLE 1308.1830, LHCb 1403.2888, LHCb 1306.2239

$$L^{\rm th}_{K^*\phi} = 22.04^{+7.06}_{-4.88} \qquad L^{\rm exp}_{K^*\phi} = 8.80^{+6.07}_{-2.97} \qquad 1.48\ \sigma$$

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2404.01186 [hep-ph]

Pseudoscalar-Vector final states

$$\mathcal{B}(\bar{B}_d \to \bar{K}^0\phi)^{\rm th} = (4.28^{+2.71}_{-1.50}) \times 10^{-6} \qquad \mathcal{B}(\bar{B}_d \to \bar{K}^0\phi)^{\rm exp} = (7.3 \pm 0.7) \times 10^{-6}$$

BABAR 1201.5897, BELLE 0307014

$$\mathcal{B}(B^- \to K^-\phi)^{\rm th} = (4.67^{+2.98}_{-1.63}) \times 10^{-6} \qquad \mathcal{B}(B^- \to K^-\phi)^{\rm exp} = (8.8^{+0.7}_{-0.6}) \times 10^{-6}$$

BABAR 1201.5897, BELLE 0412066, CDF 0502044, CLEO2 0101032

$$\mathcal{B}(B_s \to K^{*0}\bar{K}^0)^{\rm exp} + \mathcal{B}(B_s \to \bar{K}^{*0}K^0)^{\rm exp} = (1.98 \pm 0.28 \pm 0.50) \times 10^{-5}$$

$$\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^0 + c.c.)^{\rm th,} = (8.35^{+5.02}_{-2.51}) \times 10^{-6}$$

A. Biswas ,S. Descotes, J. Matias and GTX 2404.01186 [hep-ph]

Complementary observables are required experimentally to define the corresponding optimized ratios

Processes considered

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
$10^6 BR(\bar{B}_s \to K^{*0}\, \bar{K}^{*0})_L$	$4.36^{+2.23}_{-1.65}$	$2.62^{+0.85}_{-0.75}$	0.9σ
$10^6 BR(\bar{B}_d \to \bar{K}^{*0}\phi)_L$	$4.53^{+2.16}_{-1.80}$	$4.96^{+0.31}_{-0.30}$	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
$\mathbf{L_{K^*\bar{K}^*}}$	$19.53^{+9.14}_{-6.64}$	4.43 ± 0.92	2.6σ
$\mathbf{L_{K\bar{K}}}$	$26.00^{+3.88}_{-3.59}$	14.58 ± 3.37	2.4σ
$\mathbf{L_{K^*\phi}}$	$22.04^{+7.06}_{-4.88}$	$8.80^{+6.07}_{-2.97}$	1.5σ

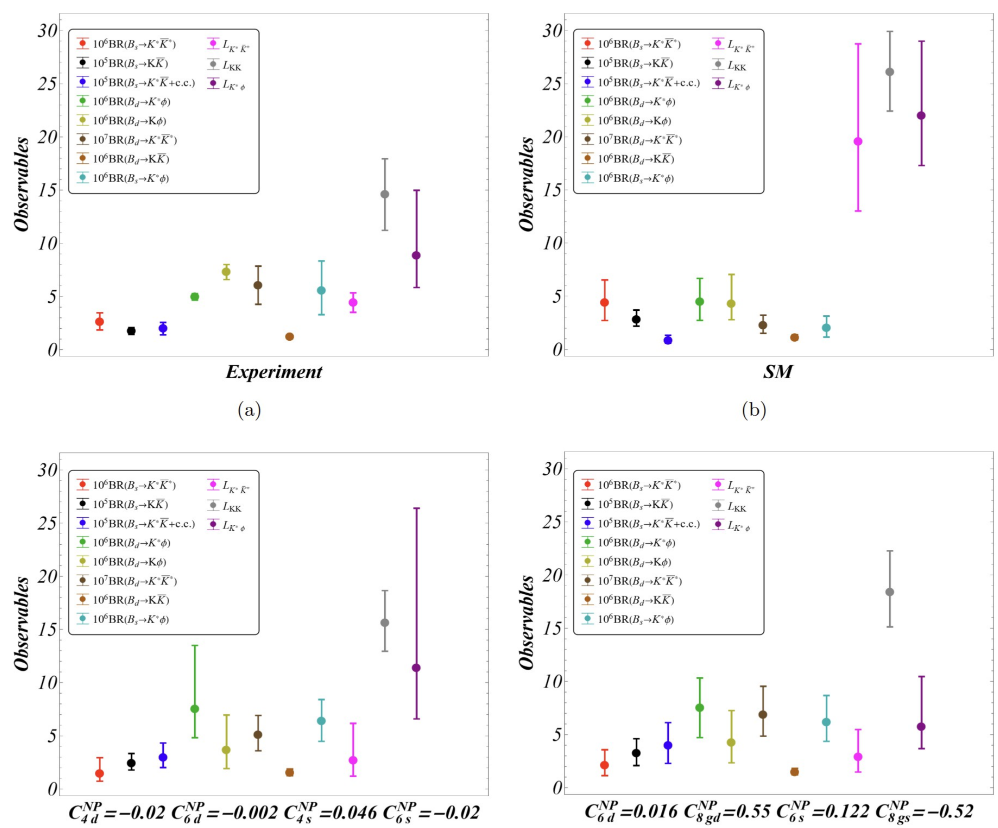
Observable	SM (QCDF)	Experiment	Deviation
$10^5(BR(\bar{B}_s \to K^{*0}\, \bar{K}^0)$ +c.c.)	$0.83^{+0.50}_{-0.25}$	$1.98 \pm 0.28 \pm 0.50$	1.4σ
$10^6 BR(\bar{B}_d \to \bar{K}^0\phi)$	$4.28^{+2.71}_{-1.50}$	7.3 ± 0.7	1.3σ
$10^6 BR(B^- \to K^{*-}\, \phi)$	$4.94^{+2.34}_{-1.91}$	$4.96^{+1.16}_{-1.08}$	*fully consistent*
$10^6 BR(B^- \to K^-\, \phi)$	$4.67^{+2.98}_{-1.63}$	$8.8^{+0.7}_{-0.6}$	1.5σ

A new puzzle in non-leptonic decays?

The New physics explanation can only be addressed by combining at least two effective operators (Q_4, Q_6) or (Q_6, Q_8) in the $b \rightarrow d$ and $b \rightarrow s$ transitions

$$Q_{4f} = (\bar{f}_i b_j)_{V-A} \sum^{q} (\bar{q}_j q_i)_{V-A}\,; \qquad Q_{6f} = (\bar{f}_i b_j)_{V-A} \sum^{q} (\bar{q}_j q_i)_{V+A} \qquad Q_{8gf} = \frac{-g_s}{8\pi^2} m_b \, \bar{f} \sigma_{\mu\nu} (1+\gamma_5) G^{\mu\nu} b$$

$$f = d, s$$



(a) (b) (c) (d)

Conclusions

Non-leptonic *B meson decay processes suffer from big uncertainties on the theory side (power corrections).*

An open problem is how to address the (power suppressed) annihilation divergences from first principles.

An possible approach is to construct optimized observables which relying on U-spin symmetry are relatively insensitive towards power correction uncertainties .

Examples of these observables are the ratios

$$L_{K^{(*)}K^{(*)}} \propto \frac{\mathcal{B}(B_s \to K^{0(*)}\bar{K}^{0(*)})}{\mathcal{B}(B_d \to K^{0(*)}\bar{K}^{0(*)})}$$

which are in tension of the experiment up to the 2.6σ level.

The tensions can be addressed in terms of NP in two operators: Q_4, Q_6 and Q_{8g} .