A new potential B-flavour anomaly in $B_{d,s} \to K^{*0}\bar{K}^{*0}$

Based on arXiv:2011.07867 - JHEP 04 (2021) 066

Portorož 2021: Physics of the flavourful Universe

Marcel Alguero, Andreas Crivellin, Sébastien Descotes-Genon, Joaquim Matias, Martín Novoa-Brunet

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

September 21, 2021

B-anomalies

- New Physics evidences in $b \to s\ell\ell$ are consistent and keep on growing.
- Natural question: In which other modes can we see signals of the NP being probed by $b \to s\ell\ell$?

B-anomalies

- New Physics evidences in $b \to s\ell\ell$ are consistent and keep on growing.
- Natural question: In which other modes can we see signals of the NP being probed by $b \to s\ell\ell$?

Connections with other modes

- Model independent: SM symmetries and flavour structure
- Model dependent: Single particle models + UV completion.

B-anomalies

- New Physics evidences in $b \to s\ell\ell$ are consistent and keep on growing.
- Natural question: In which other modes can we see signals of the NP being probed by $b \to s\ell\ell$?

Connections with other modes

- Model independent: SM symmetries and flavour structure
- Model dependent: Single particle models + UV completion.

Many modes where we can look for NP

- Neutrino FCNC ($b \to s\nu\nu$, $s \to d\nu\nu$,...)
- Up-type FCNC ($c \to u\ell\ell$)
- Non-leptonic FCNC

B-anomalies

- New Physics evidences in $b \to s\ell\ell$ are consistent and keep on growing.
- Natural question: In which other modes can we see signals of the NP being probed by $b \to s\ell\ell$?

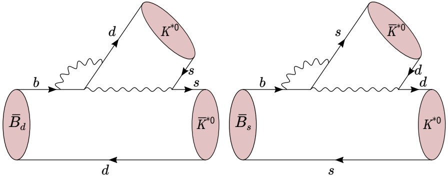
Connections with other modes

- Model independent: SM symmetries and flavour structure
- Model dependent: Single particle models + UV completion.

Many modes where we can look for NP

- Neutrino FCNC ($b \to s\nu\nu$, $s \to d\nu\nu$,...)
- Up-type FCNC ($c \to u\ell\ell$)
- Non-leptonic FCNC ⟵ **Interesting experimental results in $B_{d/s} \to K^{*0}K^{*0}$!**

$B_{d/s} \to K^{*0}\bar{K}^{*0}$



- They probe $b \to s$ and $b \to d$
- Purely penguin mediated!
- Second generation vs first generation
- Observables experimentally available:

$$\mathcal{B} = |A_0|^2 + |A_+|^2 + |A_-|^2 \qquad f_L = \frac{|A_0|^2}{|A_0|^2 + |A_+|^2 + |A_-|^2}$$

High tension for f_L with naive U-spin breaking expectation $f_L^{B_s} \sim f_L^{B_d} \pm 30\%$

$$f_L^{B_s,\mathrm{exp}} = 0.240 \pm 0.040 \qquad \text{vs} \qquad f_L^{B_d,\mathrm{exp}} = 0.734 \pm 0.039$$

Theoretical framework of $B_q \to VV$

Helicity structure

- Spin 0 $\to$ 2 $\times$ spin 1 $\Rightarrow$ 3 Helicity amplitudes (A_0, A_-, A_+)
- $V - A$ structure $\Rightarrow$ Amplitude Hierarchy (Helicity flips)

$$A_0 \; > \; A_- \; > \; A_+ \qquad \text{(naive factorisation)}$$

$\mathcal{O}(\Lambda/m_b)$ $\mathcal{O}(\Lambda/m_b)$

QCD Factorisation

- One of the main tool for treatment of non-leptonic modes.
- Profit of energy hierarchy ($m_b \gg \Lambda$) through an expansion on Λ/m_b
- Beyond naive factorisation (hard gluon corrections)

[Beneke, Buchalla, Kagan, Neubert, Sachrajda, Rohrer, Yang,...]

Main caveat: IR divergences!

Endpoint behaviour twist-3 LCDA

↓

IR divergent hard-spectator scattering and weak annihilation

↙ ↘

Longitudinal amplitude (A_0) afflicted at NLO

↓

Power suppressed!

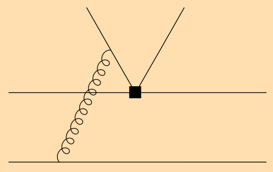
↓

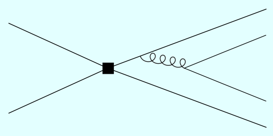
Parametrised by X_H and X_A

Transverse amplitudes ($A_\pm$) afflicted at LO

↓

Problematic!





We can only trust A_0

Analogy between semi- and non-leptonic

Semi-leptonic ($b \to s\ell\ell$)	Non-leptonic ($b \to sq\bar{q}$)
Reduce hadronic sensitivity	Reduce sensitivity to WA and HSS IR divergences
Absence of LO hadronic corrections in optimized observables	Absence of LO IR divergences in longitudinal amplitudes
LFUV ratios comparing 1st (e) and 2nd (μ) gen leptons	**U-spin** ratios comparing 1st (d) and 2nd (s) gen quarks

- Broken symmetries LFU (lepton mass) vs U-spin (quark mass)
- Corrections to U-spin are more challenging and substantially bigger (QCD) than LFUV corrections (QED)

Building a clean observable

- Build an observable depending only on A_0
- Profit of broken U-spin symmetry $\Rightarrow$ compare $f_L^{B_s}$ vs $f_L^{B_d}$

L observable

$$L_{V_1 V_2} = \frac{g_{b\to d}\mathcal{B}_{b\to s} f_L^{b\to s}}{g_{b\to s}\mathcal{B}_{b\to d} f_L^{b\to d}} = \frac{\left|A_0^s\right|^2 + \left|\bar{A}_0^s\right|^2}{\left|A_0^d\right|^2 + \left|\bar{A}_0^d\right|^2}$$

Combination of Branching ($\mathcal{B}$), longitudinal polarisation (f_L) and a phase space factor (g)

Previously introduced in a different context (R_{sd}) by [Descotes-Genon et al '12]

Amplitudes of $\bar{B}_q \to V_1 V_2$ decays

Penguin topologies

Tree and penguin topologies

$$\bar{A}_0^q \equiv A(\bar{B}_q \to V_1 V_2) = \lambda_u^{(q)} T_q + \lambda_c^{(q)} P_q$$

In our case $\Rightarrow$ only penguin topologies

Same type of IR divergences in T_q and P_q

$$\Delta_q \equiv T_q - P_q$$

Free of NLO IR divergences!

$$\bar{A}_0^q = \lambda_u^{(q)} \Delta_q - \lambda_t^{(q)} P_q$$

[Descotes-Genon, Matias, Virto '06]

L observable prediction

$$L_{K^*\bar{K}^*} = \kappa \left|\frac{P_s}{P_d}\right|^2 \underbrace{\left[\frac{1 + |\alpha^s|^2 \left|\frac{\Delta_s}{P_s}\right|^2 + 2\mathrm{Re}\left(\frac{\Delta_s}{P_s}\right) \mathrm{Re}(\alpha^s)}{1 + |\alpha^d|^2 \left|\frac{\Delta_d}{P_d}\right|^2 + 2\mathrm{Re}\left(\frac{\Delta_d}{P_d}\right) \mathrm{Re}(\alpha^d)}\right]}_{\approx 1 \pm 0.01 \text{ thanks to } \Delta_{d/s}}$$

Main Term

$$\left|\frac{P_s}{P_d}\right| = \begin{cases} 1 \pm 0.3 & \text{Naive SU(3)} \\ 0.91^{+0.20}_{-0.17} & \text{Fact SU(3)} \\ 0.92^{+0.20}_{-0.18} & \text{QCD fact} \end{cases}$$

CKM Factors

$$\kappa = \left|\frac{\lambda_c^s + \lambda_u^s}{\lambda_c^d + \lambda_u^d}\right|^2$$

$$\alpha_q = \frac{\lambda_u^q}{\lambda_c^q + \lambda_u^q}$$

L observable and tension

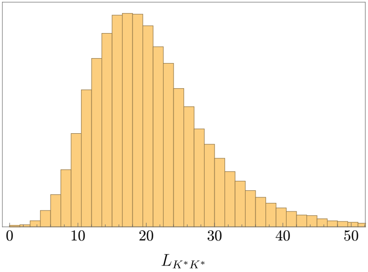
Exp	Theory	Tension
$L_{K^*\bar{K}^*} = 4.43 \pm 0.92$ [LHCb '19, BaBar '08]	$L_{K^*\bar{K}^*} = \begin{cases} 23^{+16}_{-12} & \text{Naive SU(3)} \\ 19.2^{+9.3}_{-6.5} & \text{Fact SU(3)} \\ 19.5^{+9.3}_{-6.8} & \text{QCD fact} \end{cases}$	1.9σ 3.0σ 2.6σ

Deficit in $b \to s$ vs $b \to d$!

Tension evaluation

Not Gaussian by construction:

- Montecarlo of nuisance parameters to obtain "Empirical Distribution"
- Symmetric confidence intervals



Error Budget

Input	Relative Error		
	$L_{K^*\bar{K}^*}$	$\lvert P_s\rvert^2$	$\lvert P_d\rvert^2$
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	$(-1.3\%, +1.1\%)$	$(-2.7\%, +2.5\%)$	$(-1.6\%, +1.6\%)$

Form Factors

- LCSR from BSZ
- Main error
- B_s and B_d correlations?

IR divergences

- Uncertainty of 100% and free complex phase
- Influence is substantially reduced in $L_{K^*\bar{K}^*}$
- U-spin correlation between B_s and B_d must be present (independent of parametrisation!)
- Even with X_A different for B_s and B_d error is dominated by form factors

$$X_{A,H} = (1 + \rho_{A,H} e^{i\phi_{A,H}}) \ln\left(\frac{m_B}{\Lambda_h}\right)$$

$$\rho_{A,H} \in [0,1]\,, \phi_{A,H} \in [0, 2\pi]$$

[Beneke, Buchalla, Neubert, Sachrajda '99]

New physics explanations: EFT approach

We consider only SM-like operators (and their chirally flipped versions)

$$\mathcal{H}_{\rm eff}^{b\to q} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(q)} \left(\mathcal{C}_{1q}^p \mathcal{O}_{1q}^p + \mathcal{C}_{2q}^p \mathcal{O}_{2q}^p + \mathcal{C}_{7\gamma q}\mathcal{O}_{7\gamma q} + \mathcal{C}_{8gq}\mathcal{O}_{8gq} + \sum_{i=3..10} \mathcal{C}_{iq}\mathcal{O}_{iq} \right)$$

$$\mathcal{O}_{1s}^p \;=\; (\bar{p}b)_{V-A}(\bar{s}p)_{V-A}$$

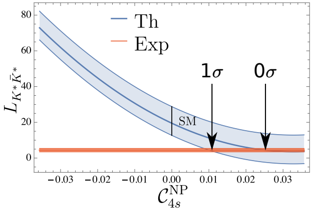
Needed: 60% Constraints: <10% [Lenz et al '20] ✗

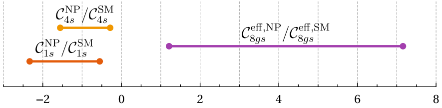
$$\mathcal{O}_{4s} \;=\; (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

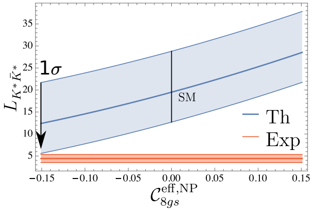
Needed: 25% Loose constraints ✓

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

Needed: 100% $b \to sg$ leaves enough room ✓







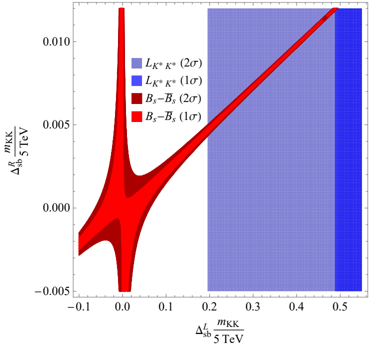
$\mathcal{C}_{8gs}^{\rm eff,\,SM} = -0.151$ $\quad\mathcal{C}_{4s}^{\rm SM} = -0.036\quad$ at $\mu = 4.2$GeV

New physics explanations: Simplified models

$\mathcal{C}_{8gs} \Rightarrow$ Complicated to generate: Loop effect to be SM order, NP coloured particles, LHC bounds

$\mathcal{C}_{4s} \Rightarrow$ Tree level NP massive $SU(3)_C$ octet vector particle ("massive gluon")

$$\mathcal{L} = \Delta^L_{qq'}\bar{q}\gamma^\mu P_L T^a q' G^a_\mu + \Delta^R_{qq'}\bar{q}\gamma^\mu P_R T^a q' G^a_\mu$$



Flavour structure $\Delta^{L(R)}_{qq'}$:

- Flavour diagonal for 1st two generations (Strongly constrained by dijet searches)
- $\Delta^{L(R)}_{sb} \neq 0$ to generate $\mathcal{C}^{\mathrm{NP}}_{4s}$

Constraints from $B_s - \bar{B}_s$ mixing:

[FLAG, Ciuchini et al '97, Buras et al '00]

- Contributions to $\mathcal{C}_{1s}$, $\mathcal{C}_{4s}$, $\mathcal{C}_{5s}$
- Significant amount of fine-tuning to explain $L_{K^*\bar{K}^*}$

Conclusions

- We present a "new" anomaly in $B_{d,s} \to K^{*0}\bar{K}^{*0}$ in what we call the $L_{K^*\bar{K}^*}$ observable.

Exp	SM QCDF	Tension
$L_{K^*\bar{K}^*} = 4.43 \pm 0.92$	$L_{K^*\bar{K}^*} = 19.5^{+9.3}_{-6.8}$	2.6σ

- Error is dominated by theory, mainly from FF.
- An understanding of the **correlations of both FF** could be of tremendous use!
- NP contribution required in $\mathcal{C}_4$ or $\mathcal{C}_{8g}$ to relieve the tension
- We have not managed to find a "simple" (single particle) model that can easily explain this without an important level of fine-tuning?

A new potential B-flavour anomaly in $B_{d,s} \to K^{*0}\bar{K}^{*0}$

Based on arXiv:2011.07867 - JHEP 04 (2021) 066

Portorož 2021: Physics of the flavourful Universe

Marcel Alguero, Andreas Crivellin, Sébastien Descotes-Genon,
Joaquim Matias, Martín Novoa-Brunet

Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

September 21, 2021

Naive Factorisation $|P_s/P_d|$

$$\text{fact SU(3)}: \left|\frac{P_s}{P_d}\right| = f = 0.91^{+0.20}_{-0.17},$$

where the $\mathrm{SU}(3)$-breaking ratio related to the form factors of interest is given by

$$f = \frac{A^s_{K^*\bar{K^*}}}{A^d_{K^*\bar{K^*}}} = \frac{m^2_{B_s} A_0^{B_s \to K^*}(0)}{m^2_{B_d} A_0^{B_d \to K^*}(0)},$$

Chirally flipped currents

Chirally flipped SM operators are "automatically included" as they contribute to amplitudes in the same way as the original operator but with a negative sign.

QCD Penguin operators

$$\mathcal{O}_{3,5} = (\bar{s}b)_{V-A}(\bar{q}q)_{V\mp A} \quad \rightarrow \tilde{\mathcal{O}}_{3,5} = (\bar{s}b)_{V+A}(\bar{q}q)_{V\pm A}$$
$$\mathcal{O}_{4,6} = (\bar{s}_i b_j)_{V-A}(\bar{q}_j q_i)_{V\mp A} \quad \rightarrow \tilde{\mathcal{O}}_{4,6} = (\bar{s}_i b_j)_{V+A}(\bar{q}_j q_i)_{V\pm A}$$

$$A_i^{\mathrm{NP}}(B \to PP) \propto C_i^{\mathrm{NP}}(\mu_b) - \tilde{C}_i^{\mathrm{NP}}(\mu_b)$$
$$A_i^{\mathrm{NP}}(B \to VP) \propto C_i^{\mathrm{NP}}(\mu_b) + \tilde{C}_i^{\mathrm{NP}}(\mu_b)$$

In $B \to VV$ decays the $\perp$ transversity and $0, \parallel$ transversity final states are P-odd and P-even, respectively, yielding

$$A_i^{NP}(B \to VV)_{0,\parallel} \propto C_i^{\mathrm{NP}}(\mu_b) - \tilde{C}_i^{\mathrm{NP}}(\mu_b)$$

$$A_i^{NP}(B \to VV)_{\perp} \propto C_i^{\mathrm{NP}}(\mu_b) + \tilde{C}_i^{\mathrm{NP}}(\mu_b)$$

[Kagan '14]

Matching of B_s mixing and $\mathcal{C}_{4s}$ to the "massive gluon" coupling

$$\mathcal{C}_1^{B_s\bar{B}_s} = \frac{1}{2m_{KK}^2}\left(\Delta_{sb}^L\right)^2 \frac{1}{2}\left(1 - \frac{1}{N_C}\right) ,$$

$$\tilde{\mathcal{C}}_1^{B_s\bar{B}_s} = \frac{1}{2m_{KK}^2}\left(\Delta_{sb}^R\right)^2 \frac{1}{2}\left(1 - \frac{1}{N_C}\right) ,$$

$$\mathcal{C}_4^{B_s\bar{B}_s} = -\frac{1}{m_{KK}^2}\Delta_{sb}^L\Delta_{sb}^R ,$$

$$\mathcal{C}_5^{B_s\bar{B}_s} = \frac{1}{N_C m_{KK}^2}\Delta_{sb}^L\Delta_{sb}^R ,$$

$$\mathcal{C}_{4s} = -\frac{1}{4}\frac{\Delta_{sb}^L\Delta_{qq}^L}{\sqrt{2}G_F V_{tb}V_{ts}^* m_{KK}^2} ,$$

Mixing Constraints: ΔM Theory vs Exp

$$\frac{\Delta M_{B_s}^{\mathrm{NP}}}{\Delta M_{B_s}^{\mathrm{SM}}} \times 10^{-10} = \left(1.1(\mathcal{C}_1^{B_s\bar{B}_s} + \tilde{\mathcal{C}}_1^{B_s\bar{B}_s}) + 8.4\mathcal{C}_4^{B_s\bar{B}_s} + 3.1\mathcal{C}_5^{B_s\bar{B}_s}\right) \mathrm{GeV}^2$$

$$\frac{\Delta M_{B_s}^{\mathrm{exp}}}{\Delta M_{B_s}^{\mathrm{SM}}} = 1.11 \pm 0.09$$

[FLAG, Ciuchini et al '97, Buras et al '00]