A puzzle in $B_{d,s} \to K^{*0}\bar{K}^{*0}$

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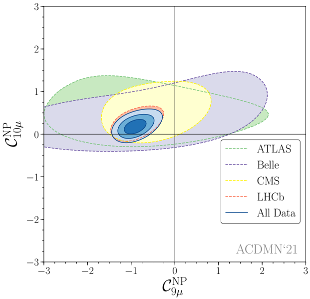
Non-leptonic B-meson decays, Siegen, 2/6/22

B-anomalies



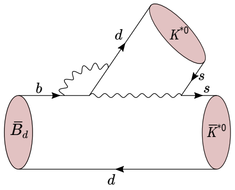
- New Physics hints in $b \to s\ell\ell$
- Other modes with signals of NP probed by $b \to s\ell\ell$?
  - Neutrino FCNC ($b \to s\nu\nu$, $s \to d\nu\nu$,...)
  - Up-type FCNC ($c \to u\ell\ell$)
  - Non-leptonic FCNC

- Interesting/puzzling 2019 LHCb results (3 fb^{-1}) in $B_{d/s} \to K^{*0}\bar{K}^{*0}$

[LHCb 1905.06662]

- Isolate appropriate observables to pin down deviations
- Approaches to explain these deviations
  - Model independent: SM symmetries and flavour structure
  - Model dependent: Single particle models + UV completion

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



- Purely penguin mediated modes, connected by U-spin
- Branching ratio and longitudinal polarisation measured:

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

expressed in terms of helicity amplitudes

- 2019 LHCb results :

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

- Deviation from naive U-spin breaking expectation $f_L^{B_s} \sim f_L^{B_d} \pm 30\%$

$B_q \to VV$ theoretical framework

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)

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

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

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

- Expansion in Λ/m_b to separate soft, collinear and hard modes
- Beyond naive fact involving U-spin breaking ratio of form factors

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

- Hard gluons, hard-spectator interaction, weak annihilation
- Central issue of $1/m_b$-suppressed corrections, some of which exhibit infrared divergences (breakdown of factorisation)

IR divergences

Endpoint behaviour twist-3 LCDA

↓

IR divergent hard-spectator scattering and weak annihilation

↙ ↘

Longitudinal amplitude (A_0) afflicted at NLO

↓

Power suppressed

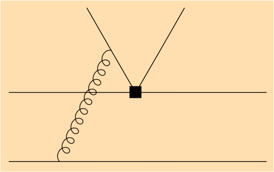
↓

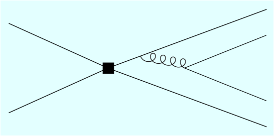
Parametrised by X_H and X_A

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

↓

Problematic





We focus on longitudinal amplitude A_0

A clean(er) observable

- Compare $f_L^{B_s}$ vs $f_L^{B_d}$ to profit from U-spin symmetry
- Build a clean(er) observable depending only on A_0

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

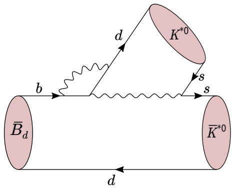
- Combination of Branching ($\mathcal{B}$), longitudinal polarisation (f_L) and a phase space factor (g)
- Previously introduced in a different context (R_{sd}) by [SDG, Matias, Virto]
- Particularly interesting in the context of penguin-mediated decays

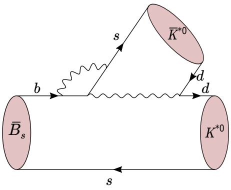
Analogy between semi- and non-leptonic decays

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

U-spin corrections more challenging and substantially bigger (QCD) than LFU corrections (QED)

Penguin-mediated decays





- $\bar{A}_0^q \equiv A(\bar{B}_q \to V_1 V_2) = \lambda_u^{(q)} T_q + \lambda_c^{(q)} P_q$ with $\lambda_U^{(q)} = V_{Ub} V_{Uq}^*$
- Penguin-mediated decays: T_q and P_q share the same structure (difference coming from the u or c quark running in the loop
- Same type of IR divergences in QCD factorisation
- $\Delta_q \equiv T_q - P_q$ is free from NLO IR divergences and well-controlled within QCD factorisation [SDG, Matias, Virto]

$$
\begin{aligned}
T_q &= A^q_{K^*K^*}[\alpha_4^u - \frac{1}{2}\alpha_{4EW}^u + \beta_3^u + 2\beta_4^u - \frac{1}{2}\beta_{3EW}^u - \beta_{4EW}^u] \\
P_q &= A^q_{K^*K^*}[\alpha_4^c - \frac{1}{2}\alpha_{4EW}^c + \beta_3^c + 2\beta_4^c - \frac{1}{2}\beta_{3EW}^u - \beta_{4EW}^c] \\
\Delta_q &= A^q_{K^*K^*}\frac{C_F\alpha_s}{4\pi N_c} C_1[\bar{G}_{K^*}(m_c^2/m_b^2) - \bar{G}_{K^*}(0)] \qquad \bar{G}_{K^*} = G_{K^*} - \frac{2m_{K^*}}{m_b}\frac{f_V^\perp}{f_V}\hat{G}_{K^*}
\end{aligned}
$$

Predicting L

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

- CKM factors $\kappa = \left|\frac{\lambda_c^s+\lambda_u^s}{\lambda_c^d+\lambda_u^d}\right|^2 \sim 22.9 \qquad \alpha_q = \frac{\lambda_u^q}{\lambda_c^q+\lambda_u^q}$
  with $\alpha_d \sim -0.01 + i0.42$, $\alpha_s \sim 0.009 - i0.018$
- Controlled hadronic $\frac{\Delta_q}{P_q}$ $\begin{cases} \frac{\Delta_d}{P_d} = (-0.16\pm 0.15) + i(0.23\pm 0.20) \\ \frac{\Delta_s}{P_s} = (-0.15\pm 0.22) + i(0.23\pm 0.25) \end{cases}$
- Dominant contribution from $\left|\frac{P_s}{P_d}\right| = \begin{cases} 1\pm 0.3 & \text{Naive SU(3)} \\ 0.91^{+0.20}_{-0.17} & \text{Fact SU(3)} \\ 0.92^{+0.20}_{-0.18} & \text{QCD fact} \end{cases}$

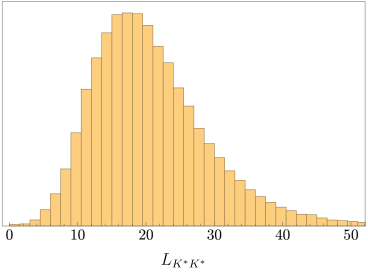
Comparing theory and experiment

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

We see a deficit in $b \to s$ vs $b \to d$

Tension evaluation

- Not Gaussian by construction
- Montecarlo of nuisance parameters to obtain an empirical distribution
- Extract confidence intervals and pull



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	$(-1.3\%, +1.1\%)$	$(-2.7\%, +2.5\%)$	$(-1.6\%, +1.6\%)$

Form Factors

- LCSR from [Bharucha, Straub, Zwicky]
- Main source of uncertainty
- Could be reduced knowing 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]

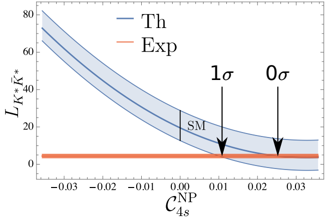
NP explanations: EFT approach

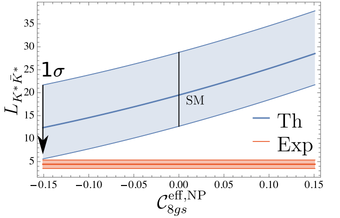
Only SM-like operators (and chirally flipped) in analogy to $b \to s\ell\ell$ fits

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

- Known QCD factorisation expressions can be used
- 3 operators explaining L with NP at most 100% of the SM
- $\mathcal{O}_{1s}^p = (\bar{p}b)_{V-A}(\bar{s}p)_{V-A}$, 60% SM needed, but constrained $< 10\%$

[Lenz, Tetlalmatzi-Xolocotzi]



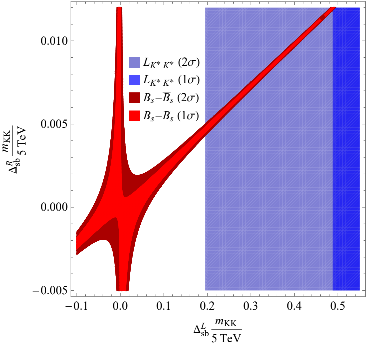


- $\mathcal{O}_{4s} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$
  25% SM needed
  only loose constraints
- $\mathcal{O}_{8gs} = \frac{-g_s m_b}{8\pi^2} \bar{s}\sigma_{\mu\nu}(1+\gamma_5) G^{\mu\nu} b$
  100% SM needed
  $b \to sg$ leaves enough room

NP explanations: Simplified models

- $\mathcal{C}_{8gs}$: Hard to generate: Loop effect (SM order), NP coloured particles, but LHC bounds unless chiral enhancement
- $\mathcal{C}_{4s}$: Tree level NP $SU(3)_C$ 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 first two gens (avoid K and D mixing, coupling constrained from dijet searches)
- $\Delta^L_{sb} \neq 0$ to generate $\mathcal{C}^{\rm NP}_{4s}$

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

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

Conclusions

- $B_{d,s} \to K^{*0}\bar{K}^{*0}$: Penguin mediated decays related by U-spin
- Good theoretical control of many ingredients
- A "new" anomaly in $L_{K^*\bar{K}^*}$ observable (longitudinal amplitudes)

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

- In QCD fact, error dominated by form factors (correlations needed)
- Supported by more naive estimates (naive factorisation, U-spin)
- Favours NP contribution in $\mathcal{C}_4$ or $\mathcal{C}_{8g}$ to relieve the tension
- No "simple" (single particle) model that can easily explain this without an important level of fine-tuning

Bonus track

Chirally flipped currents

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

- Chirally-flipped SM operators "automatically included": contribute to amplitudes as the original operator but with a negative sign [Kagan]

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

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

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

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

B_s mixing and $\mathcal{C}_{4s}$ from "massive gluon" coupling

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

- B_s Mixing

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

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

$$\mathcal{C}_4^{B_s\bar{B}_s} = -\frac{1}{m_{KK}^2}\Delta^L_{sb}\Delta^R_{sb},$$

$$\mathcal{C}_5^{B_s\bar{B}_s} = \frac{1}{N_C m_{KK}^2}\Delta^L_{sb}\Delta^R_{sb},$$

- $\mathcal{C}_{4s}$

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

Mixing Constraints

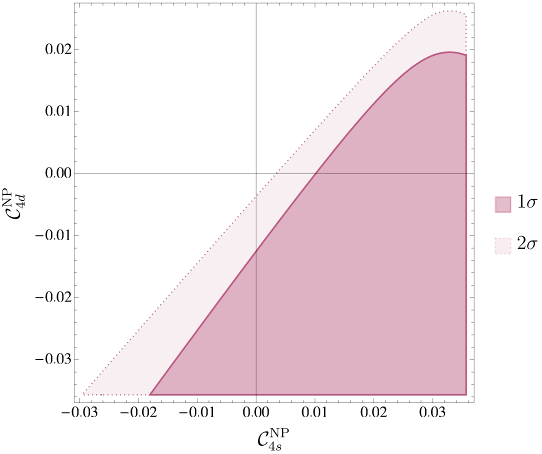
$$\mathcal{C}_1^{B_s\bar{B}_s} = \frac{1}{2m_{KK}^2}\left(\Delta_{sb}^L\right)^2 \frac{1}{2}\left(1-\frac{1}{N_C}\right),$$
$$\tilde{\mathcal{C}}_1^{B_s\bar{B}_s} = \frac{1}{2m_{KK}^2}\left(\Delta_{sb}^R\right)^2 \frac{1}{2}\left(1-\frac{1}{N_C}\right),$$
$$\mathcal{C}_4^{B_s\bar{B}_s} = -\frac{1}{m_{KK}^2}\Delta_{sb}^L\Delta_{sb}^R,$$
$$\mathcal{C}_5^{B_s\bar{B}_s} = \frac{1}{N_C m_{KK}^2}\Delta_{sb}^L\Delta_{sb}^R,$$

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

[FLAG, Ciuchini et al, Buras et al]

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

Playing with NP in both *s* and *d*



Possibility to reduce the NP contribution needed in each channel