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Anatomy of a new puzzle in the non-leptonic sector

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Outline

1. A new set of non-leptonic anomalies: Optimized L-observables

2. $L_{K^*K^*}$ for $\bar{B}_{d,s} \to K^{*0}\bar{K}^{*0}$

3. L_{KK} for $\bar{B}_{d,s} \to K^0\bar{K}^0$

4. Is there a prominent signal in the near future to confirm these anomalies? $\bar{B}_{d,s} \to K^{*0}\bar{K}^0$ and $\bar{B}_{d,s} \to K^0\bar{K}^{*0}$

5. Conclusions

What else?

Are there other interesting anomalies beyond the surviving semileptonic P_5' and $R_{D,D*}$ anomalies?

A new set of non-leptonic anomalies: Optimized L-observables

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

Theoretical framework: Helicity structure

$\bar{B}_Q \to VV$ **with** $Q = d, s$

Initial state spin 0 $\Rightarrow$ same helicity two vector mesons

Three helicity amplitudes

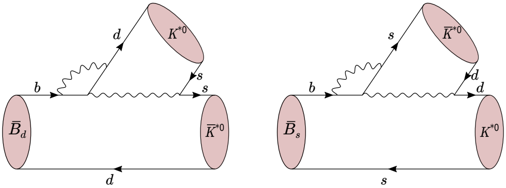
$$\bar{A}^0 > \bar{A}^- > \bar{A}^+ \qquad 1 \to \mathcal{O}(\Lambda/m_b) \to \mathcal{O}(\Lambda^2/m_b^2)$$

- V-A structure: longitudinal amplitude dominates
- In $\bar{A}^-$: one light-quark helicity flip required
- In $\bar{A}^+$: two helicity flips required

Computation using QCD Factorization:

...expansion in Λ/m_b separate hard, soft ... modes.

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



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

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

- One would expect
  - factorisation: $f_L = 1 + O(1/m_b^2)$
  - naive U-spin breaking expectation: $f_L^{B_s} \sim f_L^{B_d} \pm 30\%$
- 2019 LHCb:

$$\mathbf{f_L^{B_s,\mathrm{exp}} = 0.240 \pm 0.040} \quad \mathrm{vs} \quad \mathbf{f_L^{B_d,\mathrm{exp}} = 0.724 \pm 0.053}$$

- QCDF predictions with $\hat{\alpha}_4^{c-}$ from data:

$$\mathbf{f_L^{B_s,\mathrm{QCDF}} = 0.72^{+0.16}_{-0.21}} \quad \mathrm{vs} \quad \mathbf{f_L^{B_d,\mathrm{QCDF}} = 0.69^{+0.16}_{-0.20}}$$

Computation of the amplitude

Penguin mediated decay:

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

$$\text{where } \lambda_p^{(q)} = V_{pb} V_{pq}^*$$

Observation: Same structure and type of IR divergences in T_q and P_q $\Rightarrow$ we use $\Delta_q = T_q - P_q$ **free from NLO IR divergences.**

[S. Descotes, JM, J. Virto, PRL 97 (2006) 061801]

$$T_q = A^q_{K^*K^*}[\alpha_4^u - \frac{1}{2}\alpha^u_{4EW} + \beta_3^u + 2\beta_4^u - \frac{1}{2}\beta^u_{3EW} - \beta^u_{4EW}]$$

$$P_q = A^q_{K^*K^*}[\alpha_4^c - \frac{1}{2}\alpha^c_{4EW} + \beta_3^c + 2\beta_4^c - \frac{1}{2}\beta^u_{3EW} - \beta^c_{4EW}]$$

$$\Delta_q = A^q_{K^*K^*}\frac{C_F\alpha_s}{4\pi N_c}C_1[\bar{G}_{K^*}(m_c^2/m_b^2) - \bar{G}_{K^*}(0)] \qquad \bar{G}_{K^*} = G_{K^*} - \frac{2m_{K^*}}{m_b}\frac{f_V^\perp}{f_V}\hat{G}_{K^*}$$

Using unitarity:

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

α_i coefficients $\to$ a_i [BBNS]

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

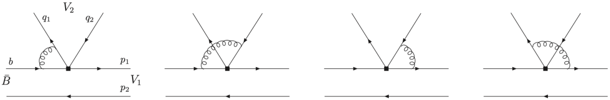


Figure 1: Vertex diagrams.

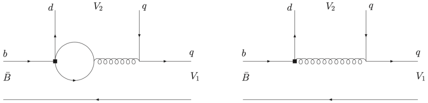


Figure 2: Penguin diagrams.

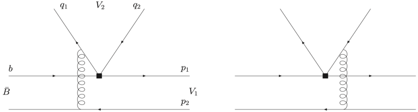


Figure 3: Hard spectator diagrams.

β_i coefficients [BBNS]

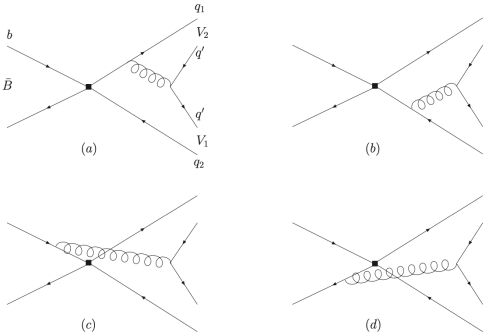
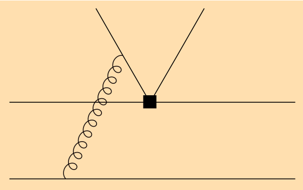


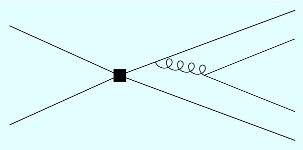
Figure 4: Annihilation diagrams.

Theoretical framework: Helicity structure

Main caveat:

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





Construction of optimized observables

Longitudinal amplitude A_0 affected by IR divergences at NLO

Transverse amplitudes ($A_\pm$) affected at LO $\Rightarrow$ Problematic predictions....

$$\Downarrow$$

Can we construct an observable out of only longitudinal amplitudes?

In non-leptonic B decays we build optimized observables by:

- **Using longitudinal amplitudes as building blocks:**
  .... absence of LO IR divergences in longitudinal amplitudes
- **Using ratios comparing 2nd gen. quarks (s) vs 1st gen. quarks (d)**
  ... to benefit from the approximate U-spin symmetry.

The L-observable

We propose in general for $\bar{B}_Q \to VV$ with $Q = d, s$ and $b \to q$:

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

- Reduced sensitivity to IR divergences and FFs SU(3) related.
- Constructed upon:
  1. Branching ratios $\mathcal{B}_{b\to s}$
  2. Phase space factor $g_{b\to q}$
  3. Polarization fraction $f_L^{b\to q}$

For the particular case $\bar{B}_Q \to K^{*0}\bar{K}^{*0}$:

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

$\rho(m_{K^{*0}}, m_{K^{*0}}) = g_{b\to d}/g_{b\to s}$

Computation of the L-observable: SM prediction

$$L_{K^*\bar{K}^*} = \kappa \left|\frac{P_s}{P_d}\right|^2 \underbrace{\left[\frac{1+|\alpha^s|^2\left|\frac{\Delta_s}{P_s}\right|^2 + 2\mathrm{Re}\left(\frac{\Delta_s}{P_s}\right)\mathrm{Re}(\alpha^s)}{1+|\alpha^d|^2\left|\frac{\Delta_d}{P_d}\right|^2 + 2\mathrm{Re}\left(\frac{\Delta_d}{P_d}\right)\mathrm{Re}(\alpha^d)}\right]}_{\approx 1\pm 0.01} \qquad \kappa = \left|\frac{\lambda_c^s+\lambda_u^s}{\lambda_c^d+\lambda_u^d}\right|^2 \sim 22.9$$

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

• Fact $SU(3)$: The $SU(3)$-breaking ratio related to FFs:

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

• QCDF uses the full α_s correction with all topologies. BBNS

B_s-meson mixing generates a small correction:

$$\frac{1+A^s_{\Delta\Gamma}y_s}{1+A^d_{\Delta\Gamma}y_d}\frac{1-y_d^2}{1-y_s^2},$$

where $y_q = \Delta\Gamma_{B_q}/(2\Gamma_{B_q})$

The L-observable: Experimental result

The 2019 LHCb analysis with 3 fb^{-1} Aaij et al JHEP 07, 032 (2019), Aubert et al. PRL 199, 081801 (2008)

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

The longitudinal polarisation of both modes has been measured:

$$\begin{aligned} f_L^{\rm LHCb}(B_d\to K^{*0}\bar{K}^{*0}) &= 0.724 \pm 0.051 \pm 0.016, \\ f_L^{\rm Babar}(B_d\to K^{*0}\bar{K}^{*0}) &= 0.80^{+0.10}_{-0.12} \pm 0.06, \end{aligned}$$

yielding an average:

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

whereas the polarisation for the $B_s \to K^{*0}\bar{K}^{*0}$ mode [LHCb] is: [Aaij:2019loz]

$$f_L(B_s\to K^{*0}\bar{K}^{*0}) = 0.240 \pm 0.031(stat) \pm 0.025(syst)\,.$$

Comparing theory and experiment

Experiment

$L_{K^*\bar{K}^*} = \mathbf{4.43 \pm 0.92}$

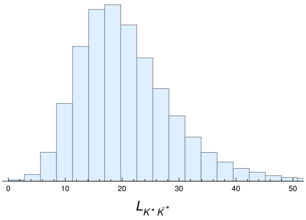
Theory

$$L_{K^*\bar{K}^*} = \begin{cases} 23^{+16}_{-12} & \text{Naive SU(3)} \quad 1.9\sigma \\ 19.2^{+9.3}_{-6.5} & \text{Fact SU(3)} \quad 3.0\sigma \\ \mathbf{19.53^{+9.14}_{-6.64}} & \text{QCD fact} \end{cases}$$

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

Tension between experiment and QCDF evaluation: 2.6σ.

- Montecarlo of nuisance parameters to obtain an empirical distribution:



L_{KK} for $\bar{B}_{d,s} \to K^0 \bar{K}^0$

Similarly we can introduce an observable for a decay to two pseudoscalars:

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

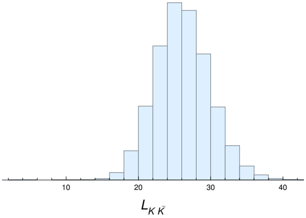
* abuse of language since no longitudinal amplitude here obviously...

$\rho(m_{K^0}, m_{K^0})$ is a ratio of phase space factors.

Its SM prediction and experimental value [Belle, Babar, LHCb]:

$$L_{K\bar{K}}^{\rm SM} = 26.00^{+3.88}_{-3.59} \qquad L_{K\bar{K}}^{\rm exp} = 14.58 \pm 3.37\,.$$

exhibiting a tension of 2.4σ.



Hypothesis:
Let's assume that NP is the explanation.

- Can one find a common NP explanation to the two L observables using an EFT language?

- Can we identify a future test for these anomalies if they come from NP?

The L-observables: model independent interpretation

Effective Hamiltonian describing $b \to s q' \bar{q}'$ with $q' = u, d, s, c, b$, and $b \to s(g, \gamma)$:

$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} \sum_{p=c,u} \lambda_p^{(q)} \left(\mathcal{C}_{1s}^p Q_{1s}^p + \mathcal{C}_{2s}^p Q_{2s}^p + \sum_{i=3\ldots 10} \mathcal{C}_{is} Q_{is} + \mathcal{C}_{7\gamma s} Q_{7\gamma s} + \mathcal{C}_{8gs} Q_{8gs} \right) .$$

$Q^p_{1s,2s}$ are the LH current-current operators, $Q_{3s\ldots 6s}$ and $Q_{7s\ldots 10s}$ are QCD and EW penguin op., and $Q_{7\gamma s}$ and Q_{8gs} are EM and chromomagnetic dipole op.

$$Q_{1s}^p = (\bar{p}b)_{V-A}(\bar{s}p)_{V-A} , \qquad Q_{7s} = (\bar{s}b)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}q)_{V+A} ,$$

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

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

$$Q_{4s} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A} , \qquad Q_{10s} = (\bar{s}_i b_j)_{V-A} \sum_q \frac{3}{2} e_q (\bar{q}_j q_i)_{V-A} ,$$

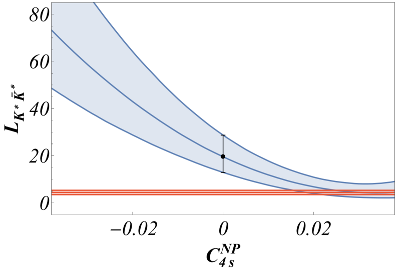
$$Q_{5s} = (\bar{s}b)_{V-A} \sum_q (\bar{q}q)_{V+A} , \qquad Q_{7\gamma s} = \frac{-e}{8\pi^2} m_b \bar{s} \sigma_{\mu\nu} (1+\gamma_5) F^{\mu\nu} b ,$$

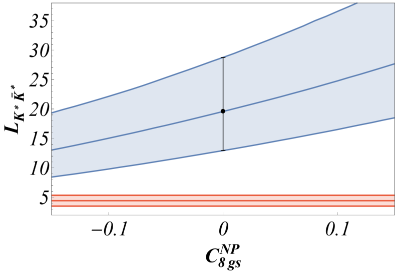
$$Q_{6s} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A} , \qquad Q_{8gs} = \frac{-g_s}{8\pi^2} m_b \, \bar{s} \sigma_{\mu\nu} (1+\gamma_5) G^{\mu\nu} b ,$$

a summation over $q = u, d, s, c, b$ is implied.

The $L_{K^*\bar{K}^*}$-observable: model independent interpretation

$\mathcal{C}^c_{1s}$ requires a 60% contribution much beyond A. Lenz constraints (10%): **discarded**





Deficit in $b \to s$ versus $b \to d$.

$$\mathcal{C}_{4s}(4.2\mathrm{GeV})^{\mathrm{SM}} = -0.036$$

- $\mathcal{O}_{4s} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$
  NP positive 25-50% SM
  $\Rightarrow$ **reduction** needed in $\mathcal{C}_{4s}$

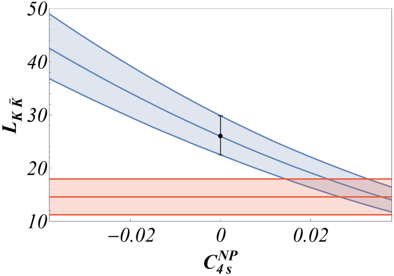
  ...only loose constraints from non-leptonic decays.

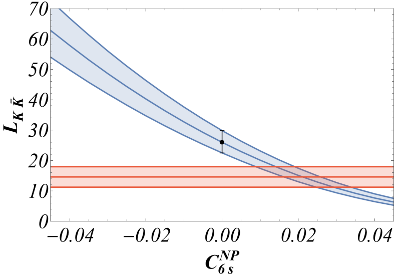
$$\mathcal{C}_{8gs}(4.2\mathrm{GeV})^{\mathrm{SM}} = -0.151$$

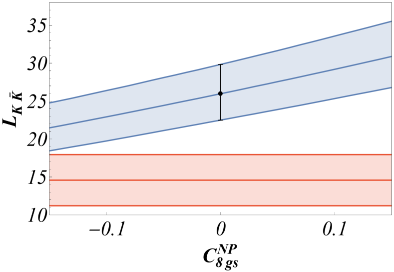
- $\mathcal{O}_{8gs} = \frac{-g_s m_b}{8\pi^2} \bar{s}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu} b$
  NP negative >100% SM needed
  $\Rightarrow$ **increase** in absolute value in $\mathcal{C}_{8gs}$

  ...inclusive nonleptonic charmless decays leaves room for $b \to sg$

The L_{KK}-observable: model independent interpretation







Same Wilson coefficients $\mathcal{C}_{4s}$, $\mathcal{C}_{8gs}$ that explains $L_{K^*\bar{K}^*}$, but also $\mathcal{C}_{6s}$.

More quantitatively using the EFT language the two L-observables are:

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

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

The three differences:

- Large $\mathcal{C}_{6s}$ term in $L_{K\bar{K}}$.
- Linear term in $\mathcal{C}_{4s}$ in $L_{K^*\bar{K}^*}$ is approx 3 times larger.
- Linear term in $\mathcal{C}_{8gs}$ in $L_{K^*\bar{K}^*}$ is approx 2 times larger.

can be traced back to:

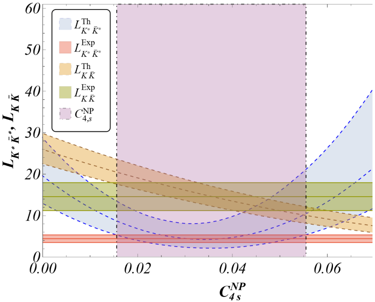
$\mathcal{C}_{4s}$: Absence of $\mathcal{C}_6 + \mathcal{C}_5/N_c$ in the V case compared to P:

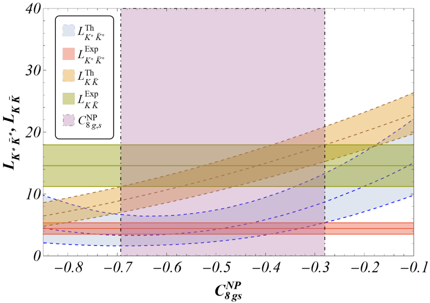
- Consequence: $L_{K,\bar{K}}^{\rm SM}$ gets enhanced and then:
  $\alpha_4^c(KK) \propto 1 - 10\mathcal{C}_{4s}^{\rm NP}$ (P) versus $\alpha_4^c(K^*K^*) \propto 1 - 30\mathcal{C}_{4s}^{\rm NP}$ (V).

$\mathcal{C}_{8gs}$: Origin in the chiral enhanced terms: absence of $P_c^6(K^*)$ contribution to $\mathcal{C}_{8gs}$.

$$\alpha_4^c(KK) \propto 1 + 0.7\mathcal{C}_{8gs}^{\rm NP} \text{ versus } \alpha_4^c(K^*K^*) \propto 1 + 1.6\mathcal{C}_{8gs}^{\rm NP}.$$

Common explanation for both observables





Magenta common region for $\mathcal{C}_{4s}$, $\mathcal{C}_{8gs}$ **if NP only in $b \to s$.**

BUT let's have a closer look to the the individual branching ratios (much less precise and reliable) ... indeed show tension in BOTH:

$\mathcal{B}(\bar{B}_d \to K^0\bar{K}^0)$ $[10^{-6}]$ **0.4σ**	
SM (QCDF)	**Experiment**
$1.09^{+0.29}_{-0.20}$	1.21 ± 0.16

$\mathcal{B}(\bar{B}_s \to K^0\bar{K}^0)$ $[10^{-5}]$ **1.6σ**	
SM (QCDF)	**Experiment**
$2.80^{+0.89}_{-0.62}$	1.76 ± 0.33

Longitudinal $\mathcal{B}(\bar{B}_d \to K^{*0}\bar{K}^{*0})$ $[10^{-7}]$ **1.8σ**	
SM (QCDF)	**Experiment**
$2.27^{+0.98}_{-0.74}$	$6.04^{+1.81}_{-1.78}$

Longitudinal $\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^{*0})$ $[10^{-6}]$ **0.9σ**	
SM (QCDF)	**Experiment**
$4.36^{+2.23}_{-1.65}$	$2.62^{+0.85}_{-0.75}$

• If one takes this info from individual branching ratios.

One natural possibility is:

$b \to s$ and $b \to d$ modes are both receiving NP contributions

- Reinterpret $L_{XX}(\mathcal{C}_{is}) \to L_{XX}(\mathcal{C}_{is} - \mathcal{C}_{id})$ with $\mathcal{C}_{id}$ expected small.
- Explore impact of individual BRs.

Allowed regions assuming NP in $b \to s$ and $b \to d$

Including the constraints from the measured L observables and individual branching ratios:

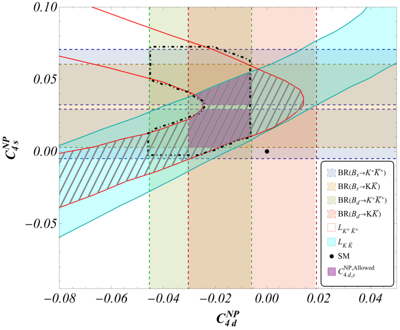


Figure: Allowed region for $\mathcal{C}^{\rm NP}_{4d}$-$\mathcal{C}^{\rm NP}_{4s}$ a) fixing $\mathcal{C}^{\rm NP}_{6d,6s} = 0$ (magenta) and b) letting $\mathcal{C}^{\rm NP}_{6d,6s}$ float freely (black dot-dashed line).

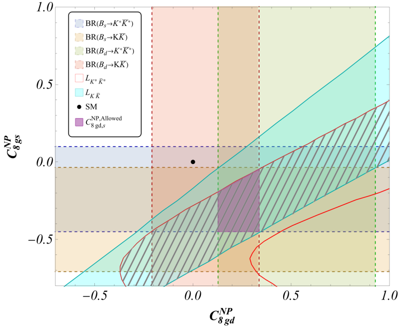
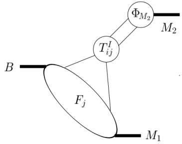


Figure: Allowed region for NP contributions to $\mathcal{C}^{\rm NP}_{8gd}$-$\mathcal{C}^{\rm NP}_{8gs}$ (magenta region).

Hatched region represents values allowed by the two measured L observables only.

Is there a prominent signal in the near future to confirm these anomalies?
$\bar{B}_{d,s} \to K^{*0}\bar{K}^0$ and $\bar{B}_{d,s} \to K^0\bar{K}^{*0}$

We can construct two (future) observables $B \to PV$ and $B \to VP$:



- $M_1 = K^{*0}$ case.

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

The SM prediction for this observable is: $\hat{L}_{K^*}^{\rm SM} = 21.30^{+7.19}_{-6.30}$

$$\hat{L}_{K^*} = 21.00 + 1040.25\, \mathcal{C}_{4s}^{\rm NP} + 12886.60\, (\mathcal{C}_{4s}^{\rm NP})^2 - 1504.72\, \mathcal{C}_{6s}^{\rm NP} + 27037.90\, (\mathcal{C}_{6s}^{\rm NP})^2 - 26.72\, \mathcal{C}_{8gs}^{\rm NP} + \ldots$$

Notice "+" in $\mathcal{C}_{4s}^{\rm NP}$ due to sign and dominance of a_{6c} over a_{4c} in $\alpha_{4c} = a_4^c - r_\chi^{M_2} a_6^c$

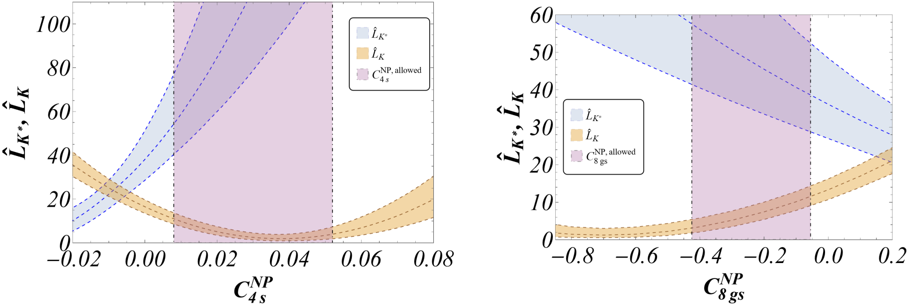
- $M_1 = K^0$ case:

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

The SM prediction for this observable is: $\hat{L}_{K}^{\rm SM} = 25.01^{+4.21}_{-4.07}$

$$\hat{L}_{K} = 25.04 - 1201.22\, \mathcal{C}_{4s}^{\rm NP} + 15994.20\, (\mathcal{C}_{4s}^{\rm NP})^2 + 149.47\, \mathcal{C}_{6s}^{\rm NP} + 66.04\, \mathcal{C}_{8gs}^{\rm NP} + \ldots$$

Including the constraints from the measured L observables and individual branching ratios:



Variation of $\hat{L}_{K^*}$ and $\hat{L}_K$:

- w.r.t $\mathcal{C}_{4s}^{\mathrm{NP}}$ for $\mathcal{C}_{4d}^{\mathrm{NP}} = -0.01$ (left)
- w.r.t $\mathcal{C}_{8gs}^{\mathrm{NP}}$ for $\mathcal{C}_{8gd}^{\mathrm{NP}} = 0.3$ (right)

Magenta are allowed regions.

These two close observables in the SM can diverge by **TWO orders of magnitude**.

But tagging for B_d modes is challenging and costly

....we may thus relax this requirement by defining observables easier to access

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

and

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

reexpressing them in terms of the optimal observables, using R_d:

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

The SM prediction for the three observables is:

$$L_{K^*}^{\rm SM} = 17.44^{+6.59}_{-5.82}, \quad L_{K}^{\rm SM} = 29.16^{+5.49}_{-5.25}, \quad R^{d\,\rm SM} = 0.70^{+0.30}_{-0.22}\,.$$

Finally, we can also consider another observable that can be accessed in the short term, but with an even more limited sensitivity to NP:

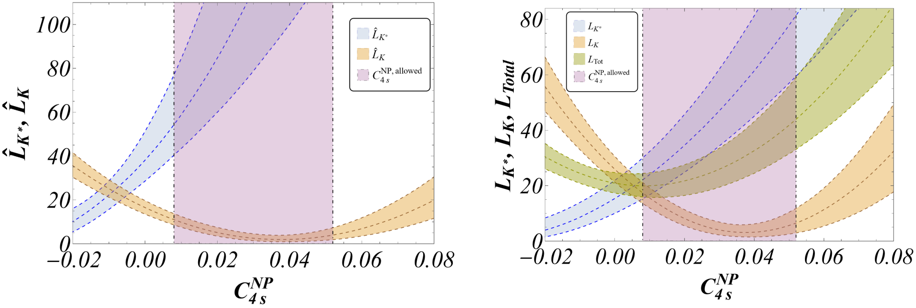
$$\begin{aligned} L_{\rm total} &= \rho(m_{K^0}, m_{K^{*0}}) \left(\frac{\mathcal{B}(\bar{B}_s \to K^{*0}\bar{K}^0) + \mathcal{B}(\bar{B}_s \to K^0\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \to \bar{K}^{*0}K^0) + \mathcal{B}(\bar{B}_d \to \bar{K}^0 K^{*0})} \right) \\ &= \frac{L_{K^*} + L_K}{2} = \frac{\hat{L}_K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

whose SM prediction is:

$$L_{\rm total}^{\rm SM} = 23.48^{+3.95}_{-3.82}.$$

$$\begin{aligned} L_{\rm total} = 23.27 &- 220.05\, \mathcal{C}_{4s}^{\rm NP} + 14633.90\, (\mathcal{C}_{4s}^{\rm NP})^2 - 574.63\, \mathcal{C}_{6s}^{\rm NP} \\ &+ 11970.70\, (\mathcal{C}_{6s}^{\rm NP})^2 + 25.44\, \mathcal{C}_{8gs}^{\rm NP} + \ldots. \end{aligned}$$

Including the constraints from the measured L observables and individual branching ratios:



Variation of L_{K^*} and L_K and $L_{\rm total}$::

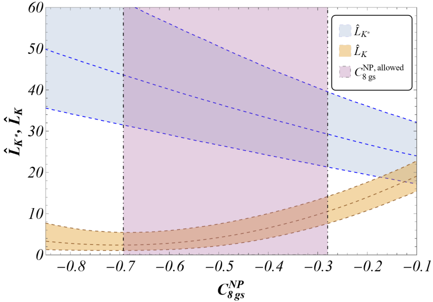
- w.r.t $\mathcal{C}_{4s}^{\rm NP}$ for $\mathcal{C}_{4d}^{\rm NP} = -0.01$

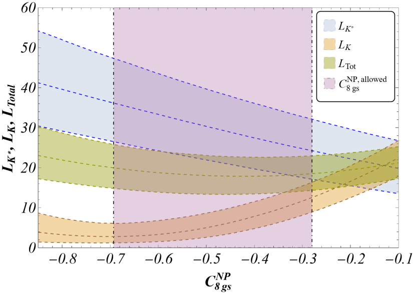
Magenta are allowed regions.

The less tagging the smaller the sensitivity:

hat observables $\rightarrow$ un-hat observables $\rightarrow$ $L_{\rm total}$

Including the constraints from the measured L observables:





Variation of L_{K^*} and L_K and $L_{\rm total}$::

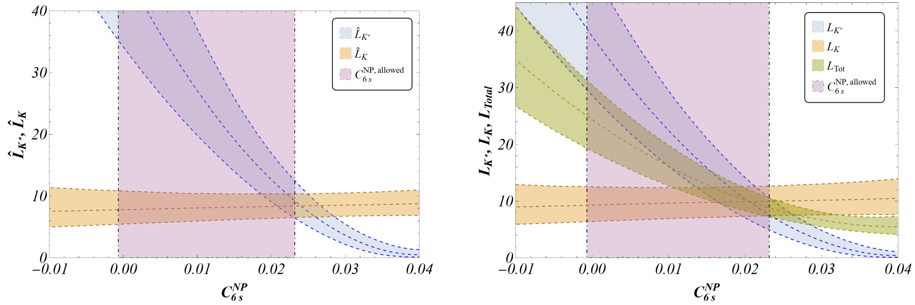
- w.r.t $\mathcal{C}_{8gs}^{\rm NP}$ with no NP in $\mathcal{C}_{8gd}^{\rm NP}$ (right), **with NP in $\mathcal{C}_{8gd}^{\rm NP}$ becomes more squeezed**

Magenta are allowed regions.

The less tagging the smaller the sensitivity:

hat observables $\to$ un-hat observables $\to$ $L_{\rm total}$

Other very singular patterns come with $\mathcal{C}_{6s}$



assuming $\mathcal{C}_{4s}^{\rm NP} = +0.020$.

...It predicts a convergence of all observables at $\mathcal{C}_{6s}^{\rm NP} \simeq +0.022$ for hat, un-hat and L_{total} observables at approx half of SM average value.

Patterns of deviations

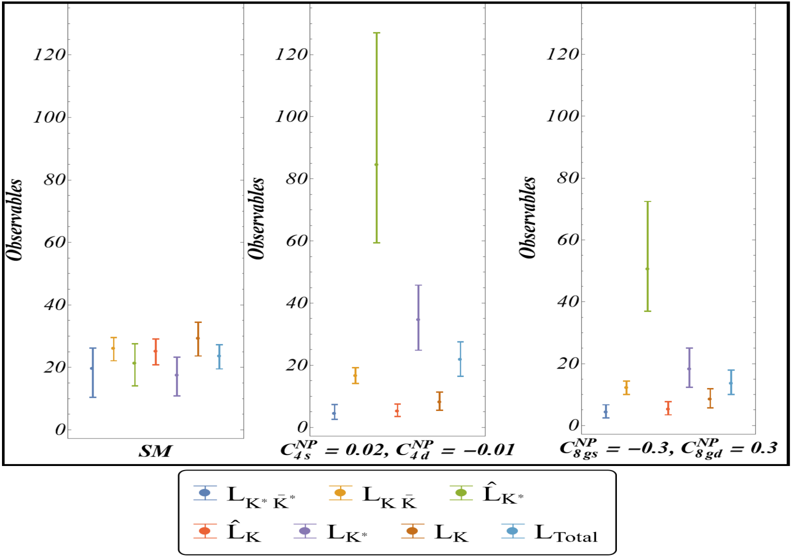


Figure: Predictions within the SM and different scenarios at specific NP points illustrating the patterns to be expected in each case, assuming NP enters both $b \to s$ and $b \to d$ transitions.

Conclusions

Conclusions

- There is life after December 2022 and intriguing anomalies are appearing also in the non-leptonic sector.

- One can construct two optimized observables $L_{K^*K^*}$ and L_{KK} exhibiting tensions of 2.6 and 2.4 σ respectively wrt SM.

- The tensions can be accommodated with a common model-independent explanation allowing for New Physics in:
  - $\mathcal{C}_{4s}$ or $\mathcal{C}_{4s}$ and $\mathcal{C}_{4d}$
  - $\mathcal{C}_{8gs}$ or $\mathcal{C}_{8gs}$ and $\mathcal{C}_{8gd}$

- Finally, we have found that in the near future a measurement of other optimized observables $\hat{L}_K$ and $\hat{L}_{K^*}$ based on $\bar{B}_{d,s} \to K^{*0}\bar{K}^0$ and $\bar{B}_{d,s} \to K^0\bar{K}^{*0}$:
  - can produce a **unique strong signal pattern** that can confirm or dismiss the tensions observed in L_{K*K*} and L_{KK}.
  - with less tagging $\Rightarrow$ less sensitivity $\Rightarrow$ easier to measure other optimized observables.

Back-up slides

Computation of the L-observable: SM prediction

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

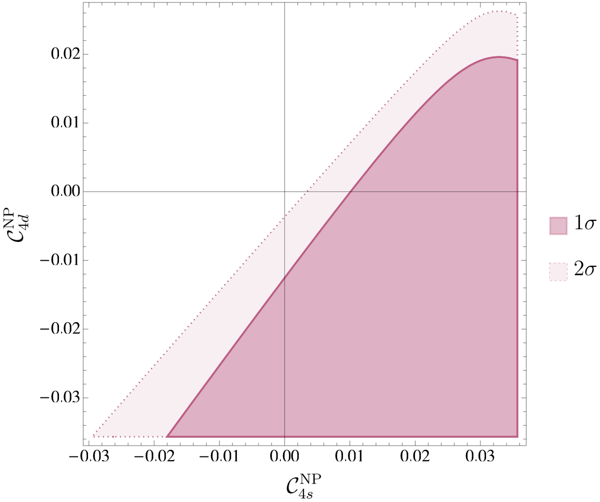
- CKM factors $\kappa = \left|\frac{\lambda_c^s + \lambda_u^s}{\lambda_c^d + \lambda_u^d}\right|^2 \sim 22.9 \qquad \alpha_q = \frac{\lambda_u^q}{\lambda_c^q + \lambda_u^q}$

  with $\alpha_d \sim -0.01 + i0.42$, $\alpha_s \sim 0.009 - i0.018$

- Suppressed hadronic $\frac{\Delta_q}{P_q} \begin{cases} \frac{\Delta_d}{P_d} = (-0.16 \pm 0.15) + i(0.23 \pm 0.20) \\ \frac{\Delta_s}{P_s} = (-0.15 \pm 0.22) + i(0.23 \pm 0.25) \end{cases}$

Also the combined solution...

Of course, a combined positive NP contribution to $\mathcal{C}_{4s}^{\rm NP}$ and negative for $\mathcal{C}_{4d}^{\rm NP}$ reduces the amount of NP (in absolute value):



The L-observable: simplified particle solution

$C_{4s} \Rightarrow$ Tree level NP massive SU(3)$_c$ octet vector particle
KK gluon (axi-gluon)

$$\mathscr{L} = \Delta^L_{sb}\bar{s}\gamma^\mu P_L T^a b G^a_\mu + \Delta^R_{sb}\bar{s}\gamma^\mu P_R T^a b G^a_\mu\,.$$

$\Delta^{L,R}_{qq}$ flavour diagonal

$$\frac{\Delta M_{B_s}^{\rm exp}}{\Delta M_{B_s}^{\rm SM}} = 1.11 \pm 0.09\,.$$

Assuming flavour diagonal coupling of KK gluon to up and down quarks of first two generations

↓

Strongly constrained by di-jet searches and K and D mixing.

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

similar for $\tilde{C}_{4s}$ with L replaced by R

The killer: $B_s - \bar{B}_s$ mixing constraint

$$
\begin{aligned}
H_{eff}^{\Delta F=2} &= \sum_{j=1}^{5} \mathcal{C}_j^{B_s\bar{B}_s} O_j^{B_s\bar{B}_s} + \sum_{j=1}^{3} \tilde{\mathcal{C}}_j^{B_s\bar{B}_s} \tilde{O}_j^{B_s\bar{B}_s} , \\
O_1^{B_s\bar{B}_s} &= [\bar{s}_\alpha \gamma^\mu P_L b_\alpha]\, [\bar{s}_\beta \gamma_\mu P_L b_\beta] , \\
O_4^{B_s\bar{B}_s} &= [\bar{s}_\alpha P_L b_\alpha]\, [\bar{s}_\beta P_R b_\beta] , \quad O_5^{B_s\bar{B}_s} = [\bar{s}_\alpha P_L b_\beta]\ [\bar{s}_\beta P_R b_\alpha] ,
\end{aligned}
$$

tilde ops exchanging $P_L \leftrightarrow P_R$. Matching contributions:

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

Using the two-loop RGE:

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

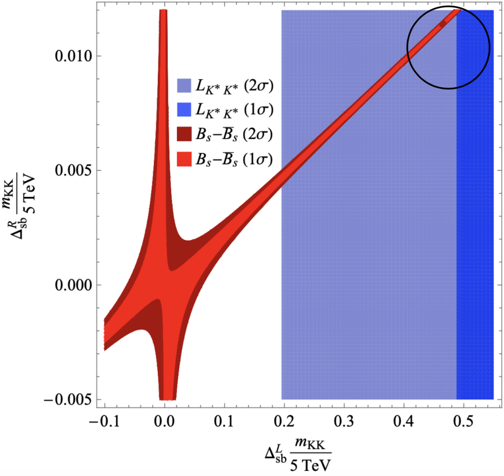
to compare with....

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

The L-observable; simplified particle solution

$C_{4s} \Rightarrow$ Tree level NP massive SU(3)c octet vector particle

KK gluon (axi-gluon)



Assuming flavour diagonal coupling of KK gluon to up and down quarks of first two generations of quarks

↓

Strongly constrained by di-jet searches and K and D mixing

↓

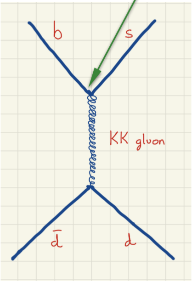
Significant amount of fine-tunning for $L_{K^*K^*}$

(if $\Delta^R_{qq} = 0$ assumed-plot)

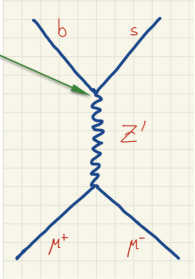
The L-observable: simplified New Physics models

Possible “link” to $b \to s\ell\ell$ anomalies…

degree of compositeness of b and s



KK gluon part of the spectrum of composite/ extra-dimensional model + Z’ **boson**



Explain $b \to s\ell^+\ell^-$ anomalies.

Explain $L_{K^*K^*}$

Future outlook

Stay tunned......

Exploring/computing other L_{XX} observables with encouraging/exciting results....
... soon in arXiv.

What is lacking? A good model to explain this anomaly and if possible connect naturally with $b \to s\ell\ell$ anomalies and R_{D,D^*}.

Remark on Δ [S. Descotes, JM, J. Virto, PRD 85 (2012) 034010]

From $\bar{A} = -\lambda_t^{(q)} T - \lambda_c^{(q)} \Delta$ with the weak phase of $\lambda_t^{(q)}$ is the β_q angle.

Combining $BR = g_{ps}(|A|^2 + |\bar{A}|^2)/2$ and three CP asymmetries $A_{\rm dir}$, $A_{\rm mix}$ and $A_{\Delta\Gamma}$

$$A_{\rm dir} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2}, \quad A_{\rm mix} \equiv -2\eta_f \frac{{\rm Im}(e^{-i\phi_Q} A^* \bar{A})}{|A|^2 + |\bar{A}|^2},$$

$$A_{\Delta\Gamma} \equiv -2\eta_f \frac{{\rm Re}(e^{-i\phi_Q} A^* \bar{A})}{|A|^2 + |\bar{A}|^2},$$

one writes these observables in terms of T, $\lambda_{c,t}^{(q)}$, Δ and ϕ_Q (B_Q meson mixing phase). Eliminating T:

$$2g_{ps}|\Delta|^2|\lambda_c^{(q)}|^2 \sin^2\beta_q = BR(1 - \eta_f \sin\Phi_{Qq} A_{\rm mix} + \eta_f \cos\Phi_{Qq} A_{\Delta\Gamma}),$$

with Φ_{Qq} defined as

$$\Phi_{Qq} = \phi_Q - 2\beta_q + \phi_Q^{\rm NP},$$

Assumption (only here): *we have assumed that NP could alter only the mixing phase of the neutral B_Q meson, but not the CKM matrix elements involved in the process.*

Example of power suppressed IR divergence

Correction from hard gluon exchange between M_2 (vertex) and spectator quark:

$$H_i(M_1M_2) = \frac{B_{M_1M_2}}{A_{M_1M_2}}\,\frac{m_B}{\lambda_B}\int_0^1 dx\int_0^1 dy\left[\frac{\Phi_{M_2}(x)\Phi_{M_1}(y)}{\bar{x}\bar{y}} + r_\chi^{M_1}\,\frac{\Phi_{M_2}(x)\Phi_{m_1}(y)}{x\bar{y}}\right]$$

1) $r_\chi^{M_1}$ suppressed by $\Lambda_{\rm QCD}/m_b$ in heavy-quark power counting.
2) Twist-3 distribution amplitude $\Phi_{m_1}(y)$ not vanishes at $y=1 \to$ divergent.

Model this divergence by defining a parameter $X_H^{M_1}$ through

$$\begin{aligned}\int_0^1 \frac{dy}{\bar{y}}\,\Phi_{m_1}(y) &= \Phi_{m_1}(1)\int_0^1\frac{dy}{\bar{y}} + \int_0^1\frac{dy}{\bar{y}}\left[\Phi_{m_1}(y)-\Phi_{m_1}(1)\right]\\ &\equiv \Phi_{m_1}(1)\,X_H^{M_1} + \int_0^1 \frac{dy}{[\bar{y}]_+}\,\Phi_{m_1}(y)\,.\end{aligned}$$

$X_H^{M_1}$ soft gluon int. spectator quark

regulated by physical scale $\Lambda_{\rm QCD} \to X_{H,A}^{M_1} \sim \left(1+\rho_{H,A}e^{i\varphi_{H,A}}\right)\mathrm{Log}(m_B/\Lambda)$

Analogy/parallelism between semi and non-leptonic decays

[M. Algueró, A. Crivellin, S. Descotes, JM, M. Novoa. JHEP 04 (2021) 066],

In $b \to s\ell\ell$ we build observables with reduced hadronic sensitivity optimized using HQS:

- Absence of LO soft FF in optimized observables (P_5') or ratios cancelling hadronic sensitivity in SM.
- LFUV ratios of 2nd gen. lepton (μ^-) vs 1st gen. lepton (e^-)

Lepton Flavour Universality in SM

In **non-leptonic B decays** we build observables optimizing them by reducing sensitivity to IR WA and HSS:

- Absence of LO IR divergences in longitudinal amplitudes
- Ratios comparing 2nd gen. quarks (s) vs 1st gen. quarks (d)

U-spin symmetry

Broken symmetries, but corrections easier in LFUV (QED) than U-spin (QCD)

Theory 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]

The L-observable: model independent interpretation

How can we incorporate *right-handed* currents?

- Chirally flipped operators $\tilde{O}_i$ are obtained:

$$V - A \leftrightarrow V + A$$

and they are included.

- The amplitudes are trivially shifted:

$$\mathcal{A}_{0,\|} \propto \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP} - \tilde{\mathcal{C}}_i^{\rm NP} \qquad \mathcal{A}_{\perp} \propto \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP} + \tilde{\mathcal{C}}_i^{\rm NP}$$

Table of inputs

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

Decay Constants (at $\mu = 2$ GeV) [?, ?, ?]			
f_{B_d}	f_{B_s}/f_{B_d}	f_{K^*}	$f_{K^*}^{\perp}/f_{K^*}$
0.190 ± 0.0013	1.209 ± 0.005	0.204 ± 0.007	0.712 ± 0.012

$B_{d,s} \to K^*$ form factors [?] and B-meson lifetimes (ps)			
$A_0^{B_s}(q^2 = 0)$	$A_0^{B_d}(q^2 = 0)$	τ_{B_d}	τ_{B_s}
0.314 ± 0.048	0.356 ± 0.046	1.519 ± 0.004	1.515 ± 0.004

Wolfenstein parameters [?]			
A	λ	$\bar{\rho}$	$\bar{\eta}$
$0.8235^{+0.0056}_{-0.0145}$	$0.22484^{+0.00025}_{-0.00006}$	$0.1569^{+0.0102}_{-0.0061}$	$0.3499^{+0.0079}_{-0.0065}$

QCD scale and masses [GeV]					
$\bar{m}_b(\bar{m}_b)$	m_b/m_c	m_{B_d}	m_{B_s}	m_{K^*}	$\Lambda_{\rm QCD}$
4.2	4.577 ± 0.008	5.280	5.367	0.892	0.225

SM Wilson Coefficients (at $\mu = 4.2$ GeV)					
$\mathcal{C}_1$	$\mathcal{C}_2$	$\mathcal{C}_3$	$\mathcal{C}_4$	$\mathcal{C}_5$	$\mathcal{C}_6$
1.082	-0.191	0.013	-0.036	0.009	-0.042
$\mathcal{C}_7/\alpha_{em}$	$\mathcal{C}_8/\alpha_{em}$	$\mathcal{C}_9/\alpha_{em}$	$\mathcal{C}_{10}/\alpha_{em}$	$\mathcal{C}_{7\gamma}^{\rm eff}$	$\mathcal{C}_{8g}^{\rm eff}$
-0.011	0.058	-1.254	0.223	-0.318	-0.151

Table: Input parameters used to determine the SM predictions.