Complementarity of $B_s \to \mu^+\mu^-$ and $B \to K\ell^+\ell^-$ decays in New Physics searches

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- $B \to K^*\gamma$, $B \to X_s\gamma$ first penguins were observed [CLEO '93, '94]
- $B \to K^*(\to K\pi)\ell^+\ell^-$, $B \to X_s\ell^+\ell^-$ (angular observables, moments)
- B_s mixing observed [CDF '06]
- CP violation in B_s mixing (compatible with small SM prediction) [D0, CDF '09, LHCb '11]
- LHCb evidence for $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
- Compatible with the SM prediction.

$$\mathcal{B}^{\rm SM} = (3.0 \pm 0.2) \times 10^{-9}$$

$\in [2.8, 44] \times 10^{-9}$ [CDF]

$< 7.7 \times 10^{-9}$ [CMS]

Motivation

- What kind of UV model can $B_s \to \mu^+\mu^-$ still hide?
- Scalar operators are the first to show up
- Turn the anticipated enhancement in supersymmetry into a strong constraint. $B_s \to \mu^+\mu^-$ can be suppressed as well.
- Very few structures enter the prediction of $\mathcal{B}(B_s \to \mu^+\mu^-)$

$$C_S - C_S', \quad C_P - C_P', \quad C_{10} - C_{10}'$$

Decay constant f_{B_s} known with good precision.

- Orthogonal to this, $B \to K\mu^+\mu^-$, probes,

$$C_S + C_S', \quad C_P + C_P', \quad C_{10} + C_{10}'$$

$+\ C^{(\prime)}_{9,T,T5}$. Hadronic form factor uncertainties are moderate.

- $C_{10}^{(\prime)}$ could be further searched for in $B \to K^*\ell^+\ell^-$

Outline

1. Introduction
2. $B_s \to \mu^+\mu^-$
3. $B \to K\mu^+\mu^-$
4. Benchmark models
   - Scalars C_S, C_S'
   - Pseudoscalars C_P, C_P'
5. C_S and C_P (SUSY)
6. Leptoquarks: $C_9^{(\prime)} \sim C_{10}^{(\prime)} \sim C_P^{(\prime)} \sim C_S^{(\prime)}$
7. Axial vector operators C_{10}, C_{10}'
8. Conclusion

$(\bar{s}\Gamma b)(\bar{\ell}\Gamma'\ell)$ effective Hamiltonian at μ_b

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \right) \right]$$

$$\mathcal{O}_7 = \frac{em_b}{g^2}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$$

$$\mathcal{O}_8 = \frac{m_b}{g}(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu,a}$$

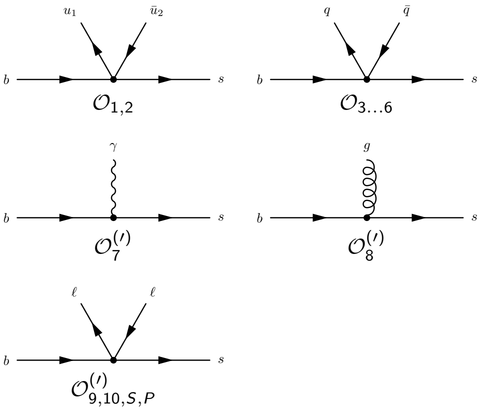
$$\mathcal{O}_9 = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}P_R b)(\bar{\ell}\ell)$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$$

$$+\,\mathcal{O}'_{7\ldots P} \text{ with } P_L \leftrightarrow P_R$$



$(\bar{s}\Gamma b)(\bar{\ell}\Gamma'\ell)$ effective Hamiltonian at μ_b

- Amplitudes are compactly represented in terms of effective Wilson coefficients

$$C_7^{\rm eff} = \frac{4\pi}{\alpha_s} C_7 - \frac{1}{3} C_3 - \frac{4}{9} C_4 - \frac{20}{3} C_5 - \frac{80}{9} C_6$$

$$C_8^{\rm eff} = \frac{4\pi}{\alpha_s} C_8 + C_3 - \frac{1}{6} C_4 + 20 C_5 - \frac{10}{3} C_6 \qquad \text{likewise for } C_i'^{\rm eff}$$

$$C_9^{\rm eff} = \frac{4\pi}{\alpha_s} C_9 \quad (+Y(q^2))$$

$$C_{10}^{\rm eff} = \frac{4\pi}{\alpha_s} C_{10}$$

- SM values, NNLL [Altmanshofer '08]

$$C_1 = -0.257 \quad C_2 = 1.009 \quad C_3 = -0.005 \quad C_4 = -0.078 \quad C_5 = 0.0 \quad C_6 = 0.001$$

$$C_7^{\rm eff} = -0.304 \qquad C_8^{\rm eff} = -0.167$$

$$C_9^{\rm eff} = 4.211 \qquad C_{10}^{\rm eff} = -4.103$$

$B_s \to \mu^+\mu^-$

- Only $C_{10}^{(\prime)}$ helicity suppressed

$$\Gamma(B_s \to \ell^+\ell^-) = \frac{G_F^2 \alpha^2}{64\pi^3} \sqrt{1 - \frac{4m_\ell^2}{m_{B_s}^2}}\, m_{B_s}^3 f_{B_s}^2 |V_{tb}V_{ts}|^2 \Big[|C_S - C_S'|^2 \frac{m_{B_s}^2}{m_b^2} (1 - 4m_\ell^2/m_{B_s}^2) + \Big| (C_P - C_P') \frac{m_{B_s}}{m_b} + \frac{2m_\ell}{m_{B_s}} (C_{10} - C_{10}') \Big|^2 \Big]$$

- Small hadronic uncertainties: $f_{B_s} = 234 \pm 6\ \mathrm{MeV}$, [Naive avg. of ETMC, Fermilab-MILC, HPQCD results]

- Prediction with $C_{10}^{\rm SM}$, while $C_{10}' = C_S^{(\prime)} = C_P^{(\prime)} = 0$

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.1 \pm 0.2) \times 10^{-9}$$

- LHCb bound

$$\mathcal{B}_{\rm exp}(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

- Finite width difference effect: [Fleischer et al, '12]

$$\frac{1}{1+|y_s|} < \frac{\mathcal{B}_{\rm exp}}{\mathcal{B}_{\rm th}} < \frac{1}{1-|y_s|}$$

- Decay with $\ell = e$ is further suppressed in the SM. Clean test of C_S, C_P.

$B \to K\ell^+\ell^-$ spectrum

$$\frac{d\Gamma}{dq^2}(B \to K\ell^+\ell^-) \sim \sqrt{\lambda(q^2)}\beta_\ell(q^2)\Big[q^2(\beta_\ell^2|F_S|^2 + |F_P|^2) + \frac{\lambda(q^2)}{6}(|F_A|^2 + |F_V|^2) + 2m_\ell(m_B^2 - m_K^2 + q^2)\mathrm{Re}\,(F_P F_A^*) + 4m_\ell^2 m_B^2|F_A|^2\Big]$$

$$F_A(q^2) = f_+(q^2)(C_{10} + C_{10}') \qquad F_S(q^2) = \frac{1}{2}\frac{m_B^2 - m_K^2}{m_b} f_0(q^2)(C_S + C_S')$$

$$F_V(q^2) = f_+(q^2)(C_9 + C_9') + \frac{2m_b}{m_B + m_K} f_T(C_7 + C_7')$$

$$F_P(q^2) = \frac{1}{2}\frac{m_B^2 - m_K^2}{m_b} f_0(q^2)(C_P + C_P') - m_\ell(C_{10} + C_{10}')\left[f_+(q^2) - \frac{m_B^2 - m_K^2}{q^2}(f_0(q^2) - f_+(q^2))\right]$$

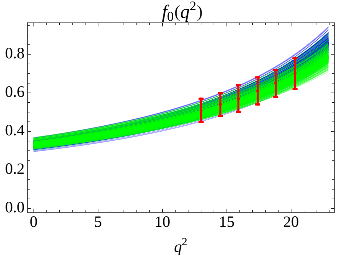
- $B \to K$ form factors

$$C_7^{(\prime)} \to f_T$$
$$C_{9,10}^{(\prime)} \to f_+(q^2), f_0(q^2)$$
$$C_{S,P}^{(\prime)} \to f_0/m_b$$

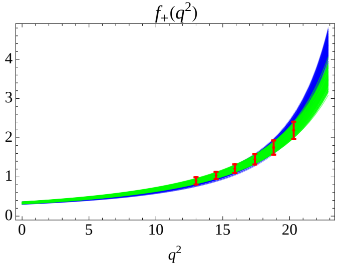
$$\langle K(k)\,|\,\bar{s}\gamma_\mu b\,|\,B(p)\rangle = \left[(p+k)_\mu - \frac{m_B^2 - m_K^2}{q^2}q_\mu\right] f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2}q_\mu f_0(q^2)$$

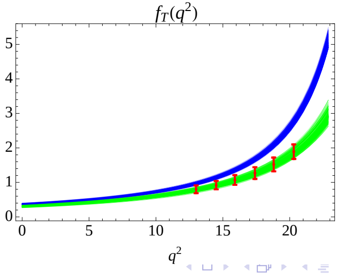
$$\langle K(k)\,|\,\bar{s}\sigma_{\mu\nu} b\,|\,B(p)\rangle = i(p_\mu k_\nu - p_\nu k_\mu)\frac{2f_T(q^2)}{m_B + m_K}$$

- Dominant uncertainties come from the form factors.
- Wide range of $q^2 \in [0, (m_B - m_K)^2]$. Opportunities for different nonperturbative techniques.

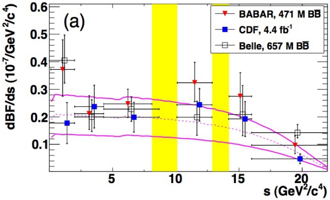


Light cone QCD sum rules [Ball '05; Khodjamirian '07],
Lattice QCD
Lattice points (quenched) [Abada '01]

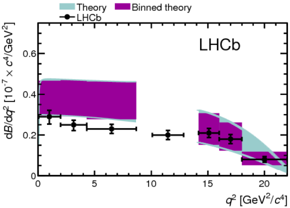




$B \to K\ell^+\ell^-$ spectrum



$\mathcal{B}(B \to K\ell^+\ell^-) = (4.7\pm0.6\pm0.2)\times10^{-7}$

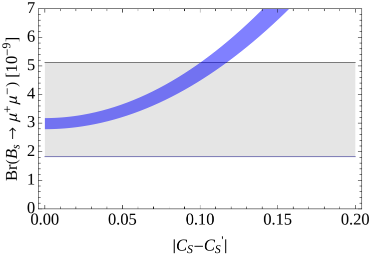


$\mathcal{B}(B \to K\mu^+\mu^-) = (4.36\pm0.33)\times10^{-7}$

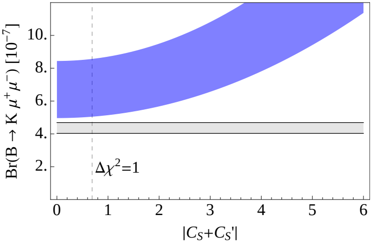
- Caveat: a sum of μ and e final states (assume lepton universality and work with μ)
- Charmonium resonances are cut out.

Scalar operators

- SM $+C_S,\ C'_S$
- $B_s \to \mu^+\mu^- \longrightarrow |C_S - C'_S|$ NO helicity suppression, enhanced wrt to the Standard part
- $B \to K\mu^+\mu^- \longrightarrow |C_S + C'_S|$



LHCb 2012, $\mathcal{B}_{\rm exp} = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$

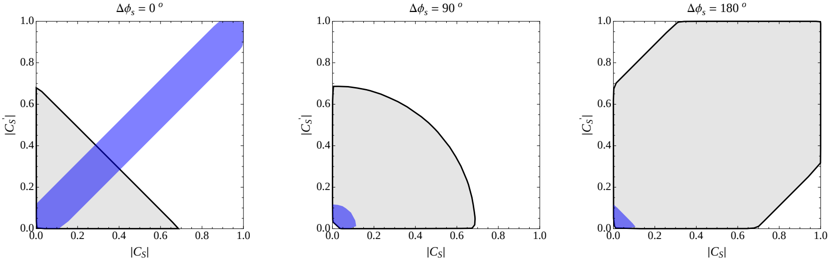


LHCb, '12
$\mathcal{B}_{B^+ \to K\mu^+\mu^-} = (4.36 \pm 0.33)\,10^{-7}$

Shrinking errors of the form factors (blue band) would aggravate existing 1.8σ tension.

Scalar operators

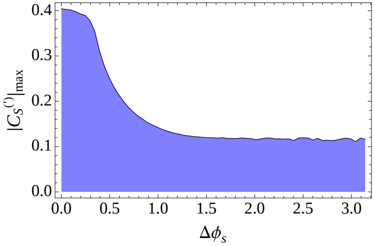
- Both regions are ellipes in $|C_S|$, $|C'_S|$ plane
- Constraints strongly depend on relative phase $\Delta\phi_S$
  (**GREY** $= B \to K\mu^+\mu^-$, **BLUE** $= B_s \to \mu^+\mu^-$)



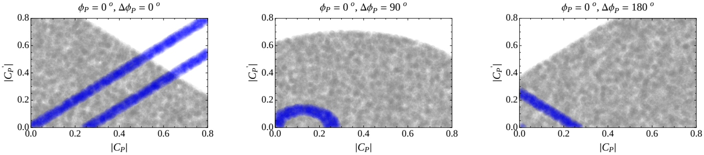
↑
cancellation $C_S - C'_S$ possible

- Inclusive $B \to X_s\mu^+\mu^-$ is less sensitive
- No transverse asymmetry in $B \to K^*\mu^+\mu^-$

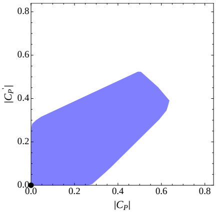
Strong constraint $|C_S^{(\prime)}| \lesssim 0.1$, unless relative phase is small



- $B_s \to \mu^+\mu^- \longrightarrow |C_P - C'_P + 2m_\ell/m_{B_s} C_{10}^{\rm SM}|$ No helicity suppression
- $B \to K\mu^+\mu^- \longrightarrow |C_P + C'_P - \# m_\ell/m_B C_{10}^{\rm SM}|$
- Relative $\Delta\phi_P$ and absolute ϕ_P phase dependence (**GREY** = $B \to K\mu^+\mu^-$, **BLUE** = $B_s \to \mu^+\mu^-$)

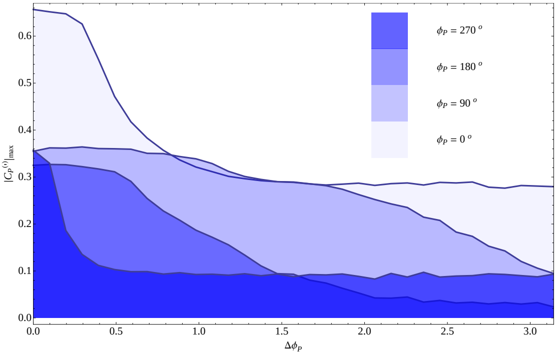


Phase-independent:



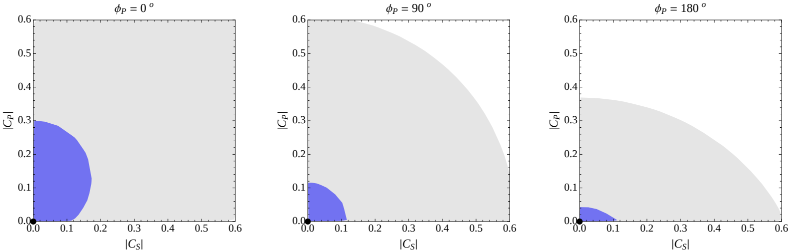
Pseudoscalar operators

$|C_P^{(\prime)}| \lesssim 0.4$ for $\mathcal{O}(1)$ relative phase.



Pseudoscalar and scalar

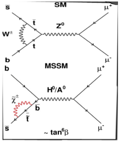
- $B_s \to \mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + 2m_\ell/m_B C_{10}^{\rm SM}|$
- $B \to K\mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + \# m_\ell/m_B C_{10}^{\rm SM}|$
- Phase of C_P enters
  (**GREY** = $B \to K\mu^+\mu^-$, **BLUE** = $B_s \to \mu^+\mu^-$)



↑
the most conservative case

- MSSM prediction at large $\tan\beta$ (dominance of H^0 penguins diagram with $\tilde{\chi}$ and $\tilde{u}$)

$$C_S, C_P \sim \tan^3\beta$$



$B \to K\mu^+\mu^-$ not as sensitive here

- $B_s \to \mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + 2m_\ell/m_B C_{10}^{\rm SM}|$
- $B \to K\mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + \# m_\ell/m_B C_{10}^{\rm SM}|$
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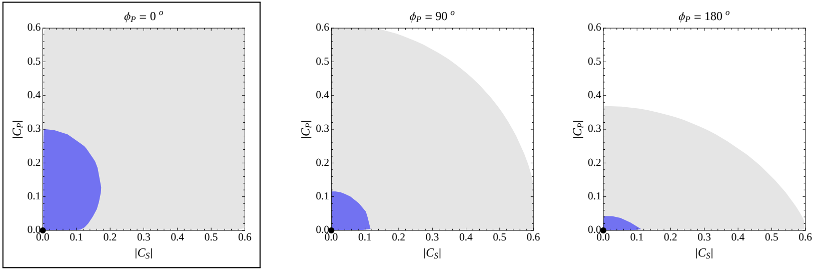

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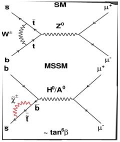

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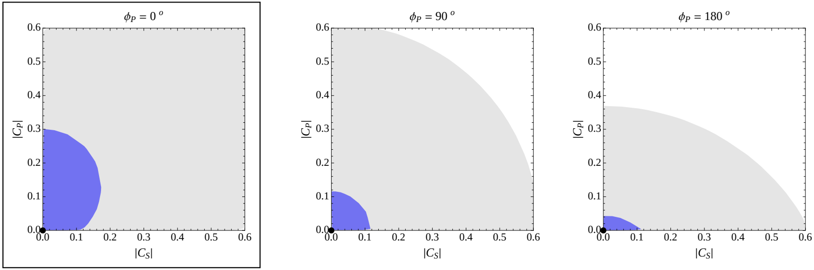
- $B \to K\mu^+\mu^- \longrightarrow |C_S|, \quad |C_P + \# m_\ell/m_B C_{10}^{\rm SM}|$
- Phase of C_P enters
  (**GREY** $= B \to K\mu^+\mu^-$, **BLUE** $= B_s \to \mu^+\mu^-$)



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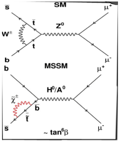
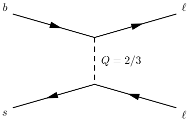


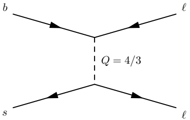
$B \to K\mu^+\mu^-$ not as sensitive here

Leptoquarks

- Possible charges:

2/3 or 4/3





- Fierz the effective operators to $(\bar{s}b)(\bar{\ell}\ell)$.
- Scalars make no scalars operators:

$$(\bar{Q}e_R)_{-7/6} \text{ and } (\bar{d}_R L)_{-1/6} \qquad \text{(charge } 2/3\text{)}$$

or

$$(\overline{Q^C}L)_{-1/3} \text{ and } (\overline{d_R^C}e_R)_{-4/3} \qquad \text{(charge } 4/3\text{)}$$

- Vectors do make scalars:

$$(\bar{Q}L)_{-2/3} \text{ and } (\bar{d}_R e_R)_{-2/3} \qquad \text{(charge } 2/3)$$

or

$$(\overline{Q^C} e)_{-5/6} \text{ and } (\overline{d_R^C} L)_{-5/6} \qquad \text{(charge } 4/3)$$

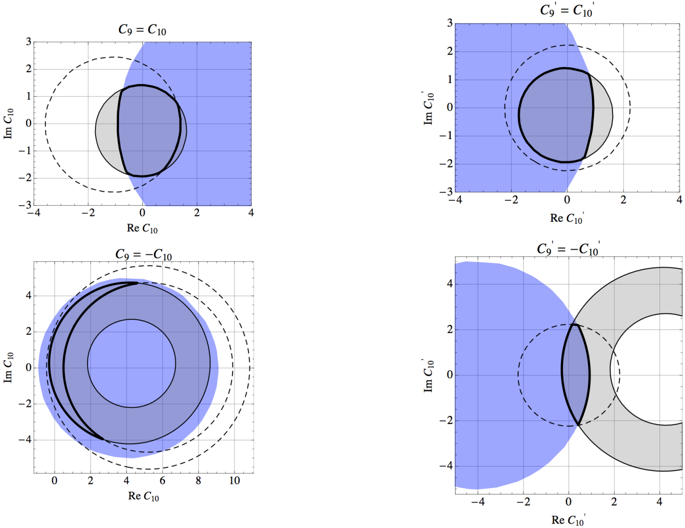
- Finite list of states

spin	$(SU(3)_C, SU(2)_L)_Y$	C_9	C_9'	C_{10}	C_{10}'	C_S	C_S'	C_P	C_P'
	$(3,2)_{7/6}$	C_{10}		C_{10}					
$S=0$	$(3,2)_{1/6} \sim \tilde{u}_L$		$-C_{10}'$		C_{10}'				
	$(\bar{3},1)_{4/3}$		C_{10}'		C_{10}'				
	$(3,3)_{2/3}$	$-C_{10}$		C_{10}					
$S=1$	$(3,1)_{2/3}$	$-C_{10}$	C_{10}'	C_{10}	C_{10}'	C_S	C_S^*	$-C_S$	C_S^*
	$(\bar{3},2)_{5/6}$	C_{10}	$-C_{10}'$	C_{10}	C_{10}'	C_S	C_S^*	$-C_S$	C_S^*

- They can all be classified as:

$$4C_{10}C_{10}' = -C_S C_S'$$

Leptoquarks

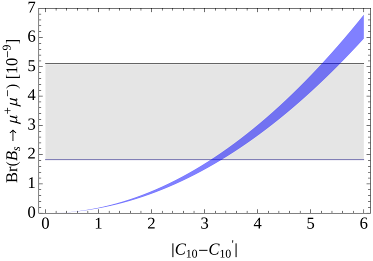


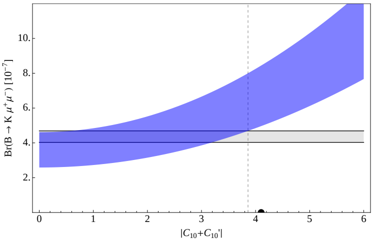
- Dashed = $B \to X_s \ell^+ \ell^-$, gray = $B \to K\mu\mu$, blue = $B_s \to \mu^+\mu^-$

Axial vector operators

$$\mathcal{O}_{10} \sim (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, \qquad \mathcal{O}_{10}' \sim (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

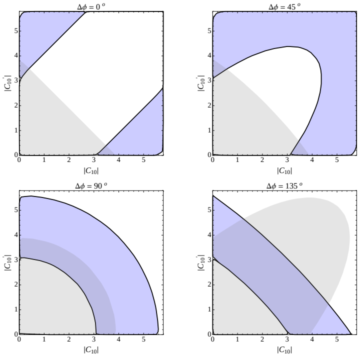
- C_{10} in the SM, C_{10}' in presence of RH currents.

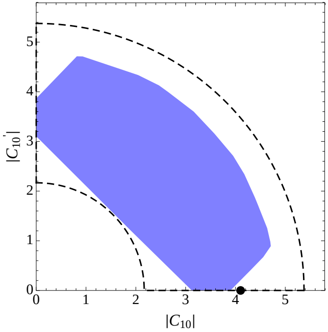




Axial vector operators

- Both regions are ellipes in $|C_{10}|$, $|C'_{10}|$ plane





- Blue $= B_s \to \mu^+\mu^-$ & grey $B \to K\mu^+\mu^-$

- Dashed $= B \to X_s \ell^+\ell^-$, blue $B \to K\mu\mu$ & $B_s \to \mu\mu$

Presence of C'_{10} can be cross-checked in $B \to K^*\mu^+\mu^-$ transverse asymmetries

A word on tensors and FB asymmetry

- We assumed NO tensor contributions to $B \to K\mu^+\mu^-$

$$\mathcal{O}_T = \frac{e^2}{16\pi^2}(\bar{s}\sigma^{\mu\nu}b)(\bar{\ell}\sigma_{\mu\nu}\ell) \qquad \mathcal{O}_{T5} = \frac{e^2}{16\pi^2}(\bar{s}\sigma^{\mu\nu}b)(\bar{\ell}\sigma_{\mu\nu}\gamma_5\ell)$$

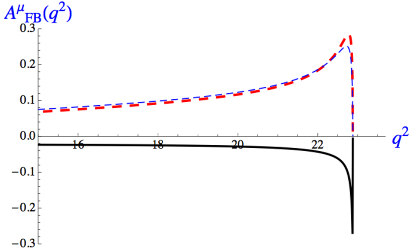
Assumption testable in

- $\mathcal{B}(B \to X_s\mu^+\mu^-)$

$$\int_{1\ \mathrm{GeV}^2}^{6\ \mathrm{GeV}^2} \frac{d\mathcal{B}(B \to X_s\mu^+\mu^-)}{dq^2}dq^2 = 1.59(17)\times 10^{-6}[1 + 0.59(2)(|C_T|^2 + |C_{T5}|^2)]$$

- Forward-backward asymmetry of $B \to K\mu^+\mu^-$

$$A^{\ell}_{FB}(q^2) = \frac{2\,\mathcal{C}(q^2)}{\Gamma_\ell}\frac{m_B - m_K}{m_b}\sqrt{\lambda(q^2)}\,f_0(q^2)\left\{ (C_S C_T + C_P C_{T5})\ q^2 f_T(q^2) \right.$$
$$\left. + m_\ell\left[C_S\ C_9(m_B + m_K)f_P(q^2) + 2m_b\,(C_S C_7 + 2C_{T5}C_{10})\,f_T(q^2)\right] + \mathcal{O}(m_\ell^2)\right\}$$



- $C_T = C_{T5} = 1.6$
- Thick $\to C_S = C_P = 0$
- Dashed $\to \{C_S, C_P\} = (1, 0)$

Conclusions

- $\mathcal{B}(B_s \to \mu^+\mu^-)$ is sensitive to (pseudo)scalar operators

$$(\bar{s}P_{L,R}b)(\bar{\ell}(\gamma_5)\ell)$$

- Only one hadronic parameter enters, f_{B_s}

- $\mathcal{B}(B \to K\ell^+\ell^-)$ is sensitive to (pseudo)scalars + vector operators (+tensors)

- With respect to $B_s \to \mu^+\mu^-$ it probes the effective Hamiltonian in the "orthogonal" direction
- Improvement in form factors calculation would make the two observables a high resolution probe of scalar operators

- For vector operators cross check is possible with spectrum of $B \to X_s\ell^+\ell^-$ and transverse asymmetries in $B \to K^*\mu^+\mu^-$

Backup

q^2-dependent contributions to $C_9^{\rm eff}$

$$
\begin{aligned}
Y(q^2) = & \frac{4}{3} C_3 + \frac{64}{9} C_5 + \frac{64}{27} C_6 - \frac{1}{2} h(q^2, 0) \left(C_3 + \frac{4}{3} C_4 + 16 C_5 + \frac{64}{3} C_6 \right) \\
& + h(q^2, m_c) \left(\frac{4}{3} C_1 + C_2 + 6 C_3 + 60 C_5 \right) - \frac{1}{2} h(q^2, m_b) \left(7 C_3 + \frac{4}{3} C_4 + 76 C_5 + \frac{64}{3} C_6 \right)
\end{aligned}
$$

$$a_\ell(q^2) = \mathcal{C}(q^2)\beta_\ell(q^2)\left[q^2(\beta_\ell^2|F_S|^2 + |F_P|^2) + \frac{\lambda(q^2)}{4}(|F_A|^2 + |F_V|^2) + 2m_\ell(m_B^2 - m_K^2 + q^2)\mathrm{Re}\,(F_P F_A^*)4m_\ell^2 m_B^2|F_A|^2\right]$$

$$c_\ell(q^2) = \mathcal{C}(q^2)\beta_\ell(q^2)\left[q^2(\beta_\ell^2|F_T|^2 + |F_{T5}|^2) - \frac{\lambda(q^2)}{4}(|F_A|^2 + |F_V|^2) + 2m_\ell\sqrt{\lambda(q^2)}\beta_\ell\mathrm{Re}\,(F_T F_V^*)4m_\ell^2 m_B^2|F_A|^2\right]$$