Hunting $\tau$-loops in $B^+ \rightarrow K^+ \mu^+ \mu^-$

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Anomalies in semileptonic $B$-decays:

$$B \rightarrow K \mu^+ \mu^-$$

FCNC ($\rightarrow$ loop level) process in the Standard Model

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**New physics** explanations favor NP mostly in the **third generation**, possible connection to the SM flavor puzzle!

$\rightarrow$ large effects in $\tau$, smaller effects in $\mu$
In these cases, one expects **large effects** from $\tau$ in $B \rightarrow K$ as well!

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- $B \to K\tau^+\tau^-$ experimentally **challenging**:
  - $\text{Br}(B^+ \to K^+\tau^+\tau^-) < 2.25 \cdot 10^{-3}$
  - $\text{Br}_{\text{SM}}(B^+ \to K^+\tau^+\tau^-) = 1.2 \cdot 10^{-7}$

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- $B_s \rightarrow \tau^+\tau^-$ likewise:
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[LHCb (2017), Phys.Rev.Lett. 118 no.25, 251802]
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There is a lot of room for new physics!

Also: Lots of data on $b \rightarrow s\mu\mu$!
**Idea:** Can we probe $b \to s\tau\tau$ through its *loop-contribution* to the $b \to s\mu\mu$ spectrum?
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![Loop Diagram]

**Based on:**

**Hunting for** $B \to K\tau^+\tau^-$ **imprints on the** $B \to K\mu^+\mu^-$ **dimuon spectrum**

*C. Cornella, G. Isidori, MK, S. Liechti, P. Owen, N. Serra*

*[in preparation]*
1. EFT description of $B \to K\ell\ell$

2. Long-distance hadronic effects

3. $\tau$-loops in $b \to s\mu\mu$

4. Sensitivity and future projections

5. Conclusions
EFT description of $B \rightarrow K\ell\ell$
EFT description

Weak effective Lagrangian: \[ \mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i \]

FCNC operators:

\[ O_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \]

\[ O_9^l = \frac{e^2}{16\pi^2} (\bar{s}\gamma_{\mu} P_L b) (\bar{l}\gamma^{\mu} l) \]

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Four-quark operators:

\[ \mathcal{O}_1^q = (\bar{s}\gamma_\mu P_L q)(\bar{q}\gamma_\mu P_L b) \]  

\[ \mathcal{O}_2^q = (\bar{s}^\alpha \gamma_\mu P_L q^\beta)(\bar{q}^\beta \gamma_\mu P_L b^\alpha) \]

Hunting \( \tau \)-loops in \( B^+ \to K^+ \mu^+ \mu^- \)
Differential decay rate:

\[
\frac{d\Gamma}{dq^2} = \frac{\alpha_{em}^2 G_F^2 |V_{tb}V_{ts}^*|^2}{128 \pi^5} \kappa_\beta \left\{ \frac{2}{3} \kappa^2 \beta^2 \left| C_{10}^{\mu} f_+(q^2) \right|^2 + \frac{4m_\mu^2 (m_B^2 - m_K^2)}{q^2 m_B^2} \left| C_{10}^{\mu} f_0(q^2) \right|^2 
+ \kappa^2 \left( 1 - \frac{1}{3} \beta \right) \left| C_9^{\mu} f_+(q^2) + 2C_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right|^2 \right\},
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Ingredients for the description:

- Perturbative short distance: matching coefficients \( C_i(\mu) \)
- Hadronic matrix elements: form factors \( f_i(q^2) \)
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Real world more complicated than that. Introduce:

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C_9^\mu \rightarrow C_9^{\text{eff}}(q^2) = C_9^\mu + Y_i(q^2)
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**short-distance SM/NP**

**long-distance QCD**

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Long-distance hadronic effects
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Leave it to QCD to make live interesting:

Depending on $q^2$, the intermediate state live at non-perturbative scales

⇒ Hadronic intermediate states rather than quarks.

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To extract bounds on a $q^2$-dependent signal, we need to understand the shape of the SM spectrum.
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Leave it to QCD to make live interesting:

\[ B^+ \rightarrow K^+ q l^- l^+ \]

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To extract bounds on a \( q^2 \)-dependent signal, we need to understand the shape of the SM spectrum.

Not a straightforward computation by first principles.
The way around: Find a region in $q^2$, where the intermediate state is dominated by short-distance physics.

Hunting $\tau$-loops in $B^+ \rightarrow K^+ \mu^+ \mu^-$
Long-distance hadronic effects

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**Example**: Charm-quark loop at $q^2 \sim 0$

Charm quarks hard ($k^2 \sim m_c^2$)

Can compute QCD corrections using the established bag of tricks

(factorizable/non-factorizable corrections, ...)
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Then: Extrapolate to high-$q^2$ region using analyticity of amplitude.

[Khodjamirian et al. (2010), JHEP 1009 089; Khodjamirian et al. (2013), JHEP 1302 010]
Leading contribution: Intermediate charmonium resonances.

\[ B^+ \rightarrow K^+ \mu^+ \mu^- \]

\[ V \in \{ J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415) \} \]
Leading contribution: Intermediate charmonium resonances.

The $q^2$-dependence is described by a relativistic Breit-Wigner.

$$\Delta Y_{c\bar{c}}^{1P}(s) = \eta_V e^{i\delta_V} \frac{s}{m_V^2} \frac{m_V \Gamma_V}{s - m_V^2 + i m_V \Gamma_V}$$

Two-particle intermediate states:
Charm loops - two-particle states

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\[ B^+ + K^+ + q \rightarrow l^- + l^+ \]

\[ B^+ + K^+ + M \rightarrow M' + l^- + l^+ \]

\( q^2 \) dependence through subtracted hadronic dispersion relation:

\[ \Delta Y_{c\bar{c}}^{2P}(s) = \frac{s}{\pi} \sum_{V} \int_{\tau_V}^{\infty} \frac{d\tilde{s}}{\tilde{s}} \frac{\rho_V(\tilde{s})}{\tilde{s} - s} \]

\( V \in \{ DD, D^* D, D^* D^* \} \)

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What are the various \( \rho_V(s) \)? → estimate!
First-principle calculation of the spectral densities $\rho_V(s)$ not viable.

\[ \rho_V = \sum c_V(4m^2 V/s), \beta(\tau) = \sqrt{1 - \tau} \]

Keeping only the leading partial waves:

\[ \rho_{DD} = (1 - 4m^2 D/s)^{3/2} \rho_{DD}^* = (1 - 4m^2 DD^*/s)^{1/2} \rho_{D^*D^*} = (1 - 4m^2 D^*/s)^{3/2} \]
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\rho_V = \sum_n c_n^V \beta^n \left( \frac{4m_V^2}{s} \right), \quad \beta(\tau) = \sqrt{1 - \tau}
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From this we find: $\rho_V = \sum_n c_n^V \beta^n (4m_V^2/s)$, $\beta(\tau) = \sqrt{1-\tau}$

Keeping only the **leading** partial waves:

$\rho_{DD} = \left(1 - \frac{4m_D^2}{s}\right)^{3/2}$  \hspace{1cm} $\rho_{DD}^* = \left(1 - \frac{4m_{DD}^2}{s}\right)^{1/2}$  \hspace{1cm} $\rho_{D^*D^*} = \left(1 - \frac{4m_{D^*}^2}{s}\right)^{3/2}$  

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\[
Y_{\text{light}}^{1P}(s) = \sum_{V} \eta_{V} e^{i\delta_{V}} \frac{m_{V} \Gamma_{V}}{s - m_{V}^2 + i m_{V} \Gamma_{V}}
\]

with \( V = \rho, \omega, \phi \).
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The hadronic long-distance contributions are written as:

$$Y_{\text{hadr}}(s) = \Delta Y_{cc}^{1P}(s) + \Delta Y_{cc}^{2P}(s) + Y_{\text{light}}^{1P}(s)$$

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We can constrain our fit by requiring $\Delta Y_{cc}^{i}(0)$ to be close to the perturbative result.
At low $q^2$, the slope of the perturbative charm contribution is:

$$
\left. \frac{d}{dq^2} \Delta Y_{cc}^{\text{pert}} \right|_{q^2=0} = \frac{4}{15m_c^2} \left( C_2 + \frac{1}{3} C_1 \right) \approx (1.7 \pm 1.7) \cdot 10^{-2} \text{GeV}^{-2}
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This yields the following set of constraints:

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\text{Re} \left[ \sum_{j=\Psi(1S),\ldots} \eta_j e^{i\delta_j} \frac{\Gamma_j}{m_j^3} + \eta_\bar{D} e^{i\delta_j} \frac{1}{6m_\bar{D}^2} + \sum_{j=D,D^*} \eta_j e^{i\delta_j} \frac{1}{10m_j^2} \right] = (1.7 \pm 2.2) \cdot 10^{-2} \text{ GeV}^{-2}
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At low $q^2$, the slope of the perturbative charm contribution is:

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Similarly, we can put an upper limit on the $\eta$ from $\Delta Y$ directly:

$$\left| \eta_{D,D^*,D} \right| \leq 0.2.$$
τ-loops in $b \rightarrow s\mu\mu$
The $\tau$ loops enter as a contribution to $C_9^{\text{eff}}(q^2)$:

$$Y_{\tau\bar{\tau}}(q^2) = -\frac{\alpha}{2\pi} C_9^{\tau} \left[ h_s \left( m_{\tau}^2, q^2 \right) - \frac{1}{3} h_p \left( m_{\tau}^2, q^2 \right) \right]$$

Intriguing channel because:
- It has an $s$-wave contribution $\rightarrow$ large
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- Again: LHCb has lots of data on $B \rightarrow K \mu\mu$!
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Tau effects in the spectrum

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With the amount of data LHCb has, we can find a bound competitive to the current one!
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Preliminary sensitivity and future

**Preliminary sensitivity:**

\[ \text{Br}(B^+ \rightarrow K^+ \tau^+ \tau^-) \lesssim 2.3 \times 10^{-3} \text{ at 95\% CL} \]

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Thank you for your attention!

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Bonus slides