

# Long-lived scalars in rare meson decays

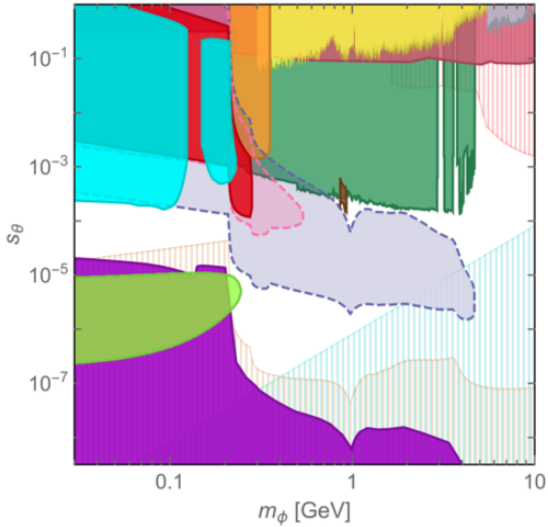
Ruth Schäfer

Heidelberg University

November 27, 2019  
6<sup>th</sup> LLPs at LHC workshop

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Based on [1911.03490] with Susanne Westhoff and Anastasiia Filimonova



[1809.01876]

# Overview

- ▶ Higgs Portal
  - ▶ Simple renormalisable extension
  - ▶ Preserves Flavour Hierarchy
- ▶ Light Scalar
  - ▶ Thermal dark matter candidates
  - ▶ Mediator of dark force
- ▶ Searches
  - ▶ Colliders/fixed-target have probed couplings  $\gtrsim 10^{-3}$
  - ▶ Astrophysics/Cosmology probe  $\lesssim 10^{-7}$
  - ▶ Belle II:  $10^{-3} - 10^{-5}$

# Higgs Portal to Dark Sector

- ▶ SM singlet scalar  $\phi$ , dark fermion  $\chi$
- ▶  $\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{m_\phi^2}{2}\phi^2 - \mu|H|^2\phi - y_\chi\bar{\chi}\chi\phi - \frac{m_\chi}{2}\chi\bar{\chi}$

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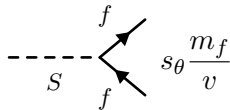
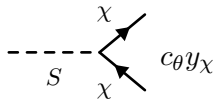
BC4 of [1901.09966]

## Scalar mixing

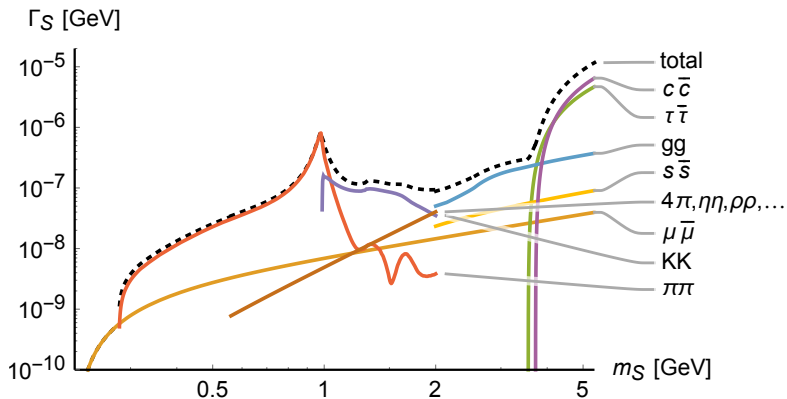
- ▶ 
$$\begin{aligned}\mathcal{L}_{\text{mass}} &= -\frac{m_\phi^2}{2}\phi^2 - \frac{m_{H_{\text{SM}}}^2}{2}H_{\text{SM}}^2 - \mu v H_{\text{SM}}\phi \\ &= -\frac{m_h^2}{2}h^2 - \frac{m_S^2}{2}S^2\end{aligned}$$
- ▶ Mass eigenstates  $h, S$
- ▶  $S = c_\theta\phi + s_\theta H_{\text{SM}}$
- ▶ Mixing angle  $s_\theta^2 = \frac{1}{2}\left(1 + \frac{m_\phi^2 - m_{H_{\text{SM}}}^2}{\Delta m^2}\right)$

## Decays of the scalar $S$

$$\blacktriangleright \Gamma_S = c_\theta^2 \Gamma_{\chi\bar{\chi}}^\phi + s_\theta^2 \Gamma_{SM}^h$$



$$\Gamma_{\chi\bar{\chi}}^S = c_\theta^2 y_\chi^2 \frac{m_S}{8\pi} \left(1 - 4 \frac{m_\chi^2}{m_S^2}\right)^{3/2} \quad \Gamma_{f\bar{f}}^S = s_\theta^2 \frac{m_f^2}{v^2} \frac{m_S}{8\pi} \left(1 - 4 \frac{m_f^2}{m_S^2}\right)^{3/2}$$

Decays of the scalar  $S$  for  $\theta = \frac{\pi}{2}$ 

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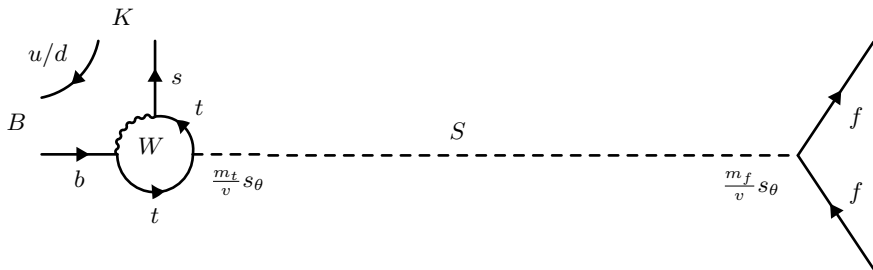
[1809.01876]

## Search regions

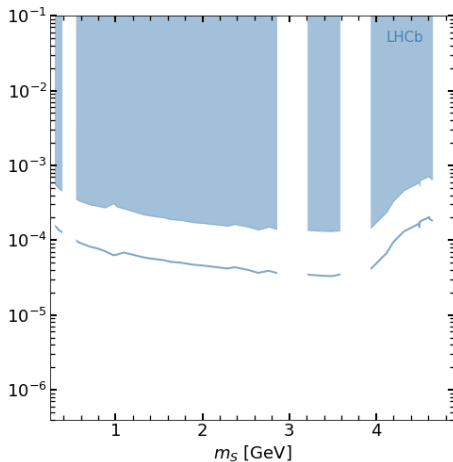
- ▶  $2m_\chi > m_S$
- ▶ No dark decay
- ▶ Displaced searches
- ▶  $2m_\chi < m_S$
- ▶ Dark decay dominant
- ▶ Search for missing energy



# Displaced Signatures



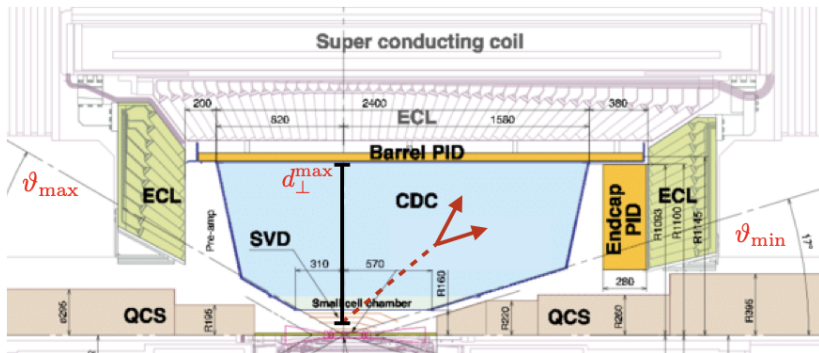
- ▶ For  $m_S = m_K$ ,  $\tau_S = \tau_{K_S}$  at a mixing angle of  $\theta \approx 5 \cdot 10^{-4}$

Displaced  $B \rightarrow K\mu\mu$  at LHCb

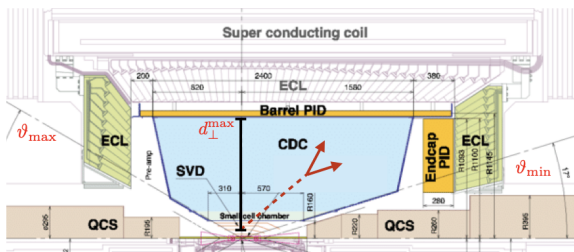
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[1612.07818], [1909.08632]

# Displaced Signatures at Belle II



# Displaced Signatures at Belle II

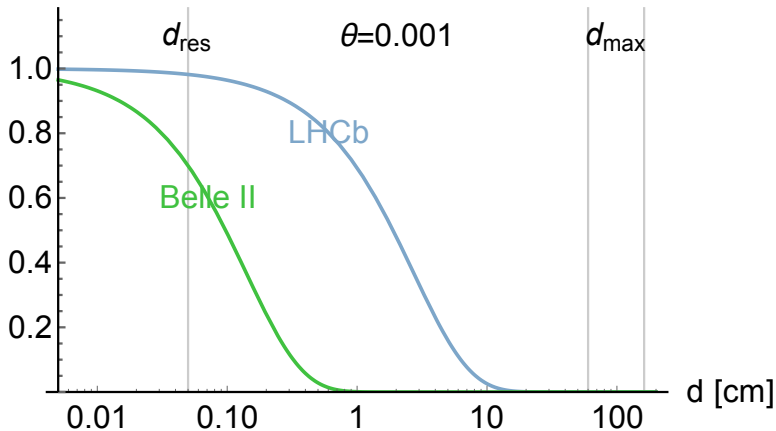


- ▶ Number of displaced  $\mu\bar{\mu}$  pairs produced

$$N_{\mu\bar{\mu}} = 2 \times N_{B\bar{B}} \times Br(B \rightarrow KS) \times Br(S \rightarrow \mu\mu) \times \int_{\vartheta_{\min}}^{\vartheta_{\max}} d\vartheta \frac{\sin\vartheta}{2} \left( \exp\left(-\frac{d_{\text{res}}}{\sin\vartheta \langle\gamma\beta\rangle c\tau}\right) - \exp\left(-\frac{r_{\text{CDC}}}{\sin\vartheta \langle\gamma\beta\rangle c\tau}\right) \right)$$

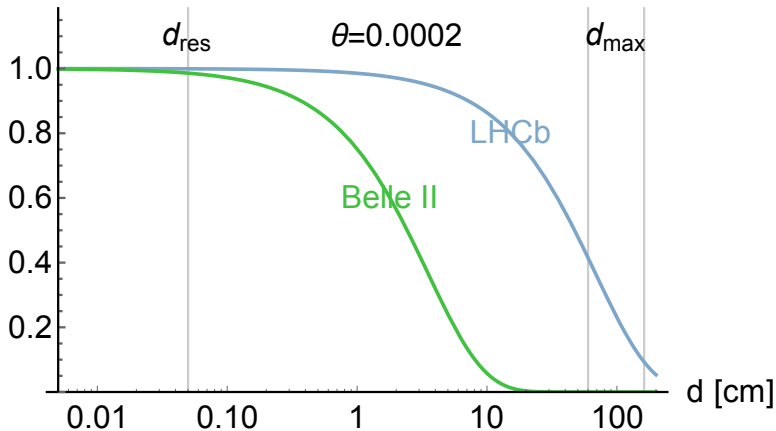
# Decay within the Detector

Yet-to-decay



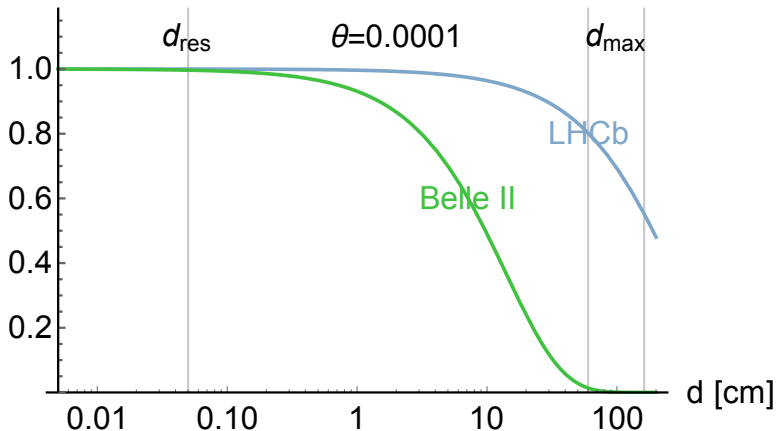
# Decay within the Detector

Yet-to-decay

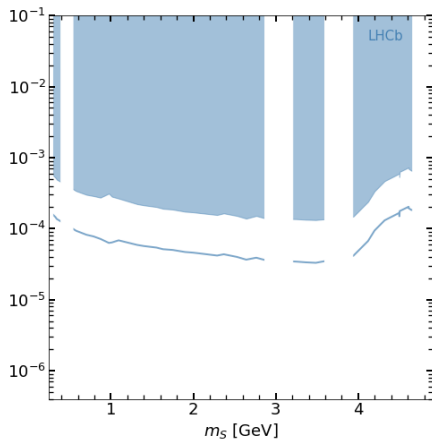


# Decay within the Detector

Yet-to-decay



# Searching for Displaced Signatures at Belle II

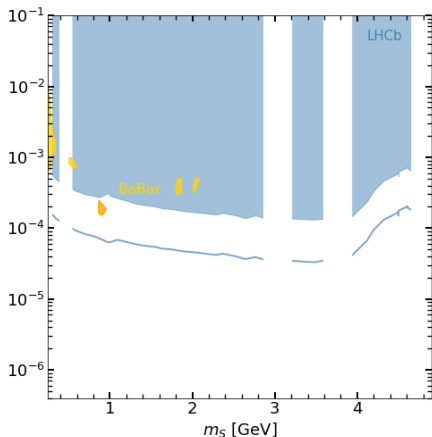


► LHCb muons

[1612.07818], [1909.08632]



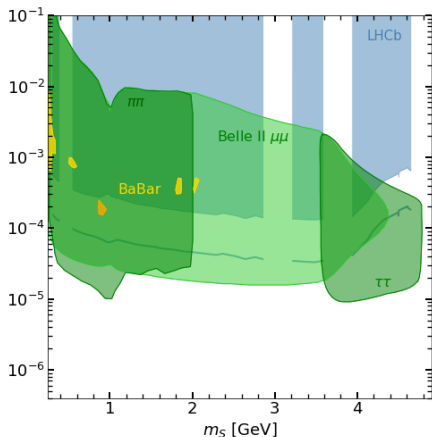
# Searching for Displaced Signatures at Belle II



- ▶ LHCb muons
- ▶ BaBar muons
- ▶ BaBar pions

[1502.02580]

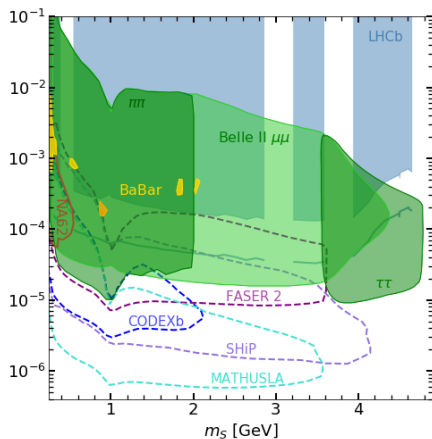
# Searching for Displaced Signatures at Belle II



[1911.03490]

- ▶ LHCb muons
- ▶ BaBar muons
- ▶ BaBar pions
- ▶ Belle II muons
- ▶ Belle II pions, taus

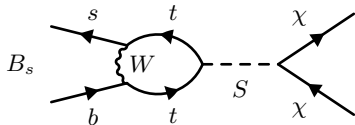
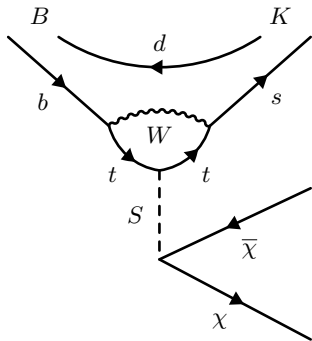
# Searching for Displaced Signatures at Belle II



- ▶ LHCb muons
- ▶ BaBar muons
- ▶ BaBar pions
- ▶ Belle II muons
- ▶ Belle II pions, taus
- ▶ FASER 2, CODEXb, SHiP, MATHUSLA, NA62

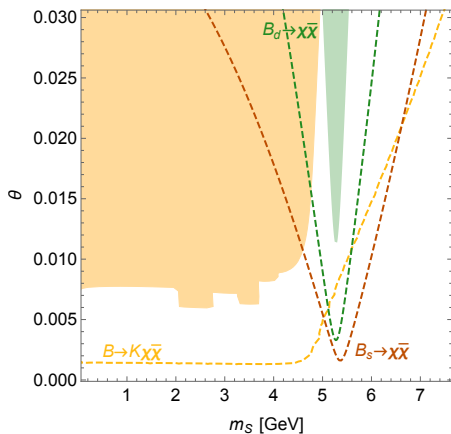
[1811.12522], [1708.09395], [1504.04855], [1708.08503], [1809.01876]

## Missing Energy Signatures



- ▶ For dominant decay to invisible:  $Br \propto s_\theta^2, \approx y_\chi$
- ▶ Missing energy final state, like neutrino searches  $B \rightarrow K \nu \bar{\nu}$

# Searching for Missing Energy Signatures at Belle II

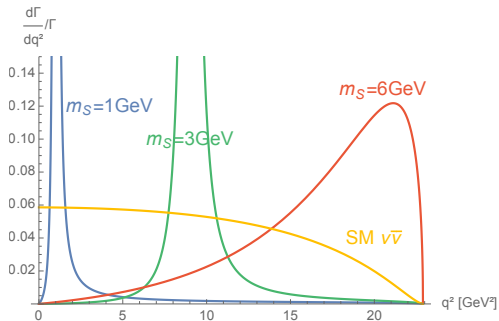


- ▶  $\frac{dBr(B \rightarrow K + \text{inv.})}{dq^2}$
- ▶  $Br(B \rightarrow K + \text{inv.})$
- ▶  $Br(B_d \rightarrow \text{inv.})$
- ▶  $Br(B_s \rightarrow \text{inv.})$

[1303.7465], [1206.5948], [1808.10567]

# Differential Branching Ratio

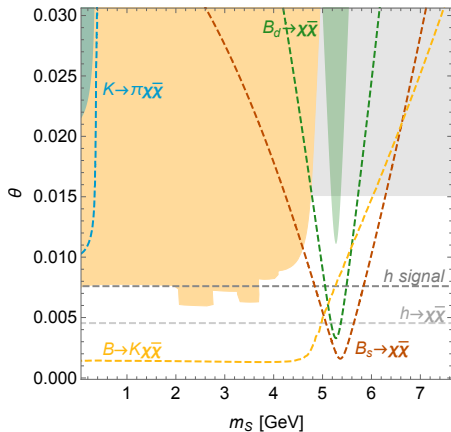
$$\blacktriangleright \frac{dBr(B \rightarrow K + \text{inv.})}{dq^2} = \frac{dBr(B \rightarrow K \nu \bar{\nu})}{dq^2} + \frac{dBr(B \rightarrow K \chi \bar{\chi})}{dq^2}$$



## Constraints from Higgs measurements

- ▶  $Br(h \rightarrow \text{inv}) = \frac{s_\theta^2 \Gamma_{\chi\bar{\chi}}^\phi}{c_\theta^2 \Gamma_{\text{SM}}^h + s_\theta^2 \Gamma_{\chi\bar{\chi}}^\phi}$
- ▶ Signal strength  $\mu = \frac{\sigma^h}{\sigma_{\text{SM}}^h} \times \frac{Br(h \rightarrow \text{vis})}{Br(h \rightarrow \text{vis})_{\text{SM}}} = c_\theta^2 \frac{c_\theta^2 \Gamma_{\text{SM}}^h}{c_\theta^2 \Gamma_{\text{SM}}^h + s_\theta^2 \Gamma_{\chi\bar{\chi}}^\phi}$

# Searching for Missing Energy Signatures at Belle II



- ▶  $\frac{dBr(B \rightarrow K + \text{inv.})}{dq^2}$
- ▶  $Br(B \rightarrow K + \text{inv.})$
- ▶  $Br(B_d \rightarrow \text{inv.})$
- ▶  $Br(B_s \rightarrow \text{inv.})$
- ▶  $K \rightarrow \pi + \text{inv.}$
- ▶  $Br(h \rightarrow \text{inv.})$
- ▶ Higgs signal strength  $\mu$

[1303.7465], [1206.5948], [1808.10567], [0808.2459], [1809.10733]



# Summary

- ▶ Rare meson decays complementary to LHC, fixed target
  - ▶ Missing Energy searches  $\theta \gtrsim 10^{-3}$
  - ▶ Displaced searches  $\theta \gtrsim 10^{-5}$