Exploring the dark sector with $B \to K^{(\star)}$ + Missing Energy

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Plan

Motivation

- Extra scalar is one of the simplest extensions of the SM.
- Light scalar can be a mediator to the Dark Sector.
- Checks of gauge dependence.
- Benchmark scenarios for Belle II experiment.

The model

- Scalar potential is described by

$$
\begin{aligned}
V &= V_H + V_{H\phi} + V_\phi + \text{h.c.} \qquad (1) \\
\text{with} \quad V_H &= -\mu^2 H^\dagger H + \frac{\bar{\lambda}_0}{4}(H^\dagger H)^2, \\
V_{H\phi} &= \frac{\alpha}{2}\phi(H^\dagger H), \\
V_\phi &= \frac{m^2}{2}\phi^2 + \frac{1}{4}\lambda_\phi \phi^4,
\end{aligned}
$$

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The model

- It is convenient to work in the mass base. Mass matrix elements defined as

$$\begin{aligned} \mu_h^2 &\equiv \frac{\partial^2 V}{\partial h^2} = \frac{\bar{\lambda}_0 v^2}{2}, \\ \mu_{h\phi}^2 &\equiv \frac{\partial^2 V}{\partial h \partial \phi} = \frac{\alpha v}{2}, \\ \mu_\phi^2 &\equiv \frac{\partial^2 V}{\partial \phi^2} = 2\lambda_\phi v_\phi^2 - \frac{\alpha v^2}{4 v_\phi}\,. \end{aligned} \quad (2)$$

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The model

- New eigenstates defined as

$$h_1 = h \cos\theta + \phi \sin\theta \,,$$
$$h_2 = -h \sin\theta + \phi \cos\theta \,. \tag{3}$$

- Vertices for the process are

$$G^+ G^- h_1 : \qquad -i \frac{e m_{h_1}^2 \cos\theta}{2 m_W \sin\theta_W} \,,$$
$$G^+ G^- h_2 : \qquad i \frac{e m_{h_2}^2 \sin\theta}{2 m_W \sin\theta_W} \,. \tag{4}$$

The model

- The process is described by diagrams

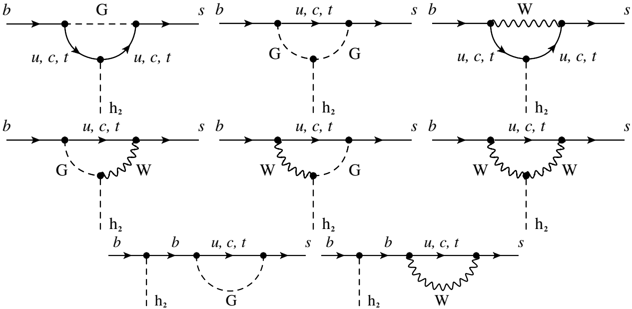


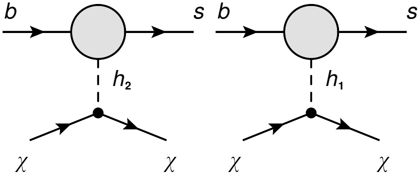
Figure: One-loop diagrams contributing to $b \to sh_2$ in R_ξ gauge.

Gauge cancellation

- For off-shell light scalar h_2, these diagrams are not only required to describe the process.
- The fermion DM is described by

$$\mathcal{L}_\chi = \lambda_\chi \phi \overline{\chi} \chi \,. \tag{5}$$

- The full set of diagrams for the process $b \to s\chi\chi$

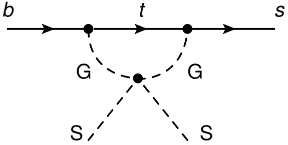


Gauge cancellation

- The scalar DM is described by

$$\mathcal{L}_S = \kappa_S \phi S^2 \,. \tag{6}$$

- An additional diagram to this process



Results

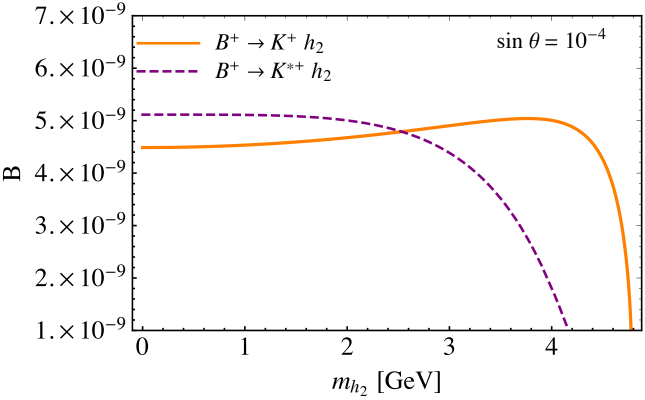


Figure: The branching fractions of $B^+ \to K^+ h_2$ (thick orange curve) and $B^+ \to K^{\star +} h_2$ (dashed purple curve) for $\sin\theta = 10^{-4}$.

Results

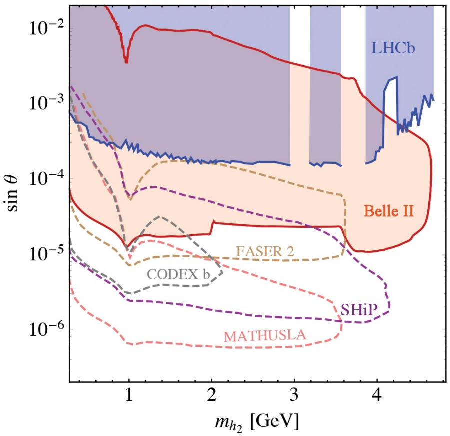


Figure: Sensitivity of the *Belle II* experiment to decay h_2 into the SM particles, including both $B \to Kh_2$ and $B \to K^* h_2$ and decays of h_2 to $(\pi\pi + KK), \mu^+\mu^-, \tau^+\tau^-$ are shown with the filled red region, and compared to the search limit of *LHCb*(shaded blue)

Results

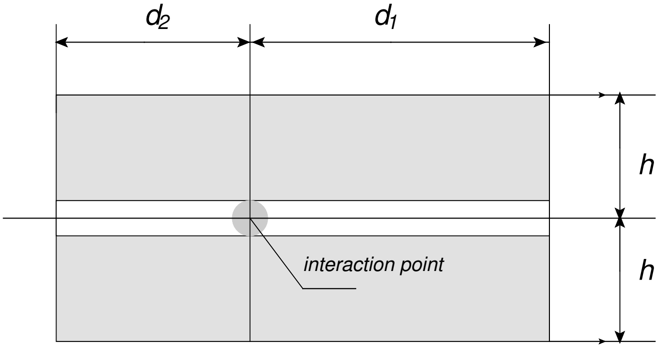


Figure: Schematic illustration of *Belle II* detector geometry. d_1 is the dimension of the detector along the z-direction measured from the interaction point to the front side, d_2 is the dimension of the detector along the z-direction measured from the interaction point to the backside, and h is the height measured from the beam line. In the evaluation have been used $d_1 = 1.5$ m, $d_2 = 0.74$m, $h = 1.17$ m.

Results

- The number of displaced vertices which can be detected in *Belle II* experiment

$$
\begin{aligned}
N_f^{\rm tot} &= N_{B\bar{B}} 1.93\, Br(B^\pm \to K^{(\star)\pm} h_2) Br(h_2 \to f) \\
&\times \int d\vartheta\, p(\vartheta) \frac{1}{d_L} \int_{r_{\rm min}(\vartheta)}^{r_{\rm max}(\vartheta)} dr \exp\left[-\frac{r}{d_L} \right].
\end{aligned}
\tag{7}
$$

Results

m_{h_2} [GeV]	τ [ps]				
	250	500	1000	2000	4000
0.3	50204	18385	5734	1614	429
0.9	972.3	465	191.8	65.7	19.6
1.5	1634.7	815.2	382.7	152.7	50.9
2.1	334.2	167.6	82.6	36.8	13.7
2.7	115.6	58	29	13.9	5.8
3.3	56.8	28.6	14.4	7.1	3.2
3.9	58.4	29.6	14.9	7.4	3.6

Table: Total number N_f^{tot} of displaced-vertex $B \to K^{(\star)} h_2[\to f]$ events in the detector of *Belle II* according to Eq. 7 for various values of the proper lifetime (columns) and mass (rows) of h_2. Here is taken into account all possible final state for the mesons K and $K^{\star}$.

Conclusions

- To use Wilson coefficient without further analysis could provide gauge dependent result.
- In wide range of parameters scalar particle can be detected in Belle II experiment.