Analysis of $B \to KM_X$ and $B \to K^*M_X$ decays in scalar- and vector-mediator dark-matter scenarios

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Motivation

In the SM $B^+ \to K^+ M_X$ is reduced to $B^+ \to K^+ \bar{\nu}\nu$. This is an FCNC (flavour-changing neutral current) induced processes which is forbiden in the SM at the tree level and occurs via loops (penguins and boxes). It has been calculated with rather good accuracy (Becirevic et al, PLB 2024):

$$\begin{aligned} Br(B^+ \to K^+ \bar{\nu}\nu) &= (4.44 \pm 0.30) \cdot 10^{-6} \\ Br(B^+ \to K^{*+} \bar{\nu}\nu) &= (9.8 \pm 1.4) \cdot 10^{-6} \end{aligned}$$

[In these numbers the contributions of the tree process $B \to \bar{\nu}(\tau \to \nu K)$ has been subtracted. This is the relevant quantity to be compared with the exp data).]

In 2017 Belle reported upper limits (for charged mesons):

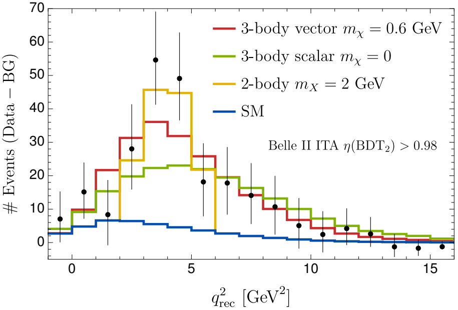
$$\begin{aligned} Br(B \to K \bar{\nu}\nu) &< 1.6 \cdot 10^{-5} \\ Br(B^* \to K^* \bar{\nu}\nu) &< 2.7 \cdot 10^{-5} \\ Br(B \to \pi \bar{\nu}\nu) &< 0.8 \cdot 10^{-5} \\ Br(B^* \to \rho \bar{\nu}\nu) &< 2.8 \cdot 10^{-5} \end{aligned}$$

with no surprises.

A great surprise comes in 2023 [Belle, PRD109,112006 (2024)]

$$Br(B^+ \to K^+ \bar{\nu}\nu) = (2.3 \pm 0.7) \cdot 10^{-5}$$
$$= (5.4 \pm 1.5) Br(B^+ \to K^+ \bar{\nu}\nu)_{\mathrm{SM}}$$

Also the differential distribution in $q^2 = (p_B - p_K)^2$ has been measured



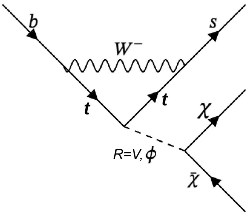
Many attempts to explain the excess within different new physics scenarios.

Our approach

We are testing a conjecture that the excess events are due to the decay into dark-matter (DM) fermions (χ) interacting with top quark via a mediator field R (top-philic mediator scenarios).

$$\Gamma(B \to KM_X) = \Gamma(B \to K\bar{\nu}\nu)_{\rm SM} + \Gamma(B \xrightarrow{R} K\bar{\chi}\chi).$$

The mediator R interacts with the top quark so the $B \to K\bar{\chi}\chi$ decay proceeds via the top-W loop:



A scalar mediator $R = \phi$ (S-scenario) and a vector mediator $R = V$ (V-scenario) are considered.

S-scenario

$$\mathcal{L}_{\rm int} = -\frac{y m_t}{v}\phi\bar{t}t - \kappa\phi\bar{\chi}\chi$$

Integrating out top and W, one obtains the effective $b \to s\phi$ Lagrangian

$$\mathcal{L}_{b\to s\phi} = g_{b\to s\phi}\phi\bar{s}_L b_R + \text{h.c.},$$

$$g_{b\to s\phi} = \frac{y m_b}{v}\frac{3\sqrt{2}G_F m_t^2 V_{ts}^* V_{tb}}{16\pi^2}$$

This $\mathcal{L}_{b\to s\phi}$ determines the $B \to (K, K^*)\bar{\chi}\chi$ amplitude proceeding via ϕ mediator. The (non-perturbative) QCD contribution is given by

$$\langle K|\bar{s}_L b_R|B\rangle = \frac{1}{2}\frac{M_B^2 - M_K^2}{m_b - m_s} f_0^{B\to K}(q^2)$$

$$\langle K^*|\bar{s}_L b_R|B\rangle = -i(\varepsilon q)\frac{M_{K^*}}{m_b + m_s} A_0^{B\to K^*}(q^2),$$

where the form factors are known.

- The differential distributions for $B \to (K, K^*)\bar{\chi}\chi$ are easily calculable

$$\frac{d\Gamma}{dq^2}(B \to K\bar{\chi}\chi) = \frac{\lambda^{1/2}(M_B^2, M_K^2, q^2)}{16\pi M_B^3} \frac{(M_B^2 - M_K^2)^2 |f_0^{B\to K}(q^2)|^2}{4(m_b - m_s)^2} \frac{g_{b\to s\phi}^2\ \kappa^2}{(M_\phi^2 - q^2)^2 + M_\phi^2 \Gamma_\phi^2(q^2)} \frac{q^2}{16\pi^2} \left(1 - \frac{4m_\chi^2}{q^2}\right)^{3/2}$$

$$\frac{d\Gamma}{dq^2}(B \to K^*\bar{\chi}\chi) = \frac{\lambda^{3/2}(M_B^2, M_{K^*}^2, q^2)}{16\pi M_B^3} \frac{|A_0^{B\to K^*}(q^2)|^2}{4(m_b + m_s)^2} \frac{g_{b\to s\phi}^2\ \kappa^2}{(M_\phi^2 - q^2)^2 + M_\phi^2 \Gamma_\phi^2(q^2)} \frac{q^2}{16\pi^2} \left(1 - \frac{4m_\chi^2}{q^2}\right)^{3/2}$$

$$\Gamma_\phi(q^2) = \frac{M_\phi}{\sqrt{q^2}} \left(\frac{q^2 - 4m_\chi^2}{M_\phi^2 - 4m_\chi^2}\right)^{\frac{3}{2}} \Theta(q^2 - 4m_\chi^2)\ \Gamma_\phi^0, \qquad \Gamma_\phi^0 = \frac{\kappa^2}{8\pi} M_\phi (1 - 4m_\chi^2/M_\phi^2)^{3/2}.$$

These distributions are sensitive to DM parameters M_ϕ, m_χ, $g_{b\to s\phi}$, κ. May be determined by a fit to the data.

- A powerful probe of the scenario (i.e. of the mediator spin):

$$\frac{d\Gamma_{B\to K^*\bar{\chi}\chi}/dq^2}{d\Gamma_{B\to K\bar{\chi}\chi}/dq^2} = \frac{\lambda(M_B^2, M_{K^*}^2, q^2)^{3/2}}{\lambda(M_B^2, M_K^2, q^2)^{1/2}} \left[\frac{m_b - m_s}{(m_b + m_s)(M_B^2 - M_K^2)}\right]^2 \left(\frac{A_0^{B\to K^*}(q^2)}{f_0^{B\to K}(q^2)}\right)^2$$

Is not sensitive to DM parameters (cancel in the ratio), but sensitive to the mediator spin!

V-scenario

One of the top-philic vector mediator scenarios is

$$\mathcal{L}_{\rm int} = g_{Vtt}\, V^\mu\, \bar{t}\gamma_\mu(1+\gamma_5)t + \kappa\, V^\mu\, \bar{\chi}\gamma_\mu\chi.$$

Integrating out top and W leads to

$$\mathcal{L}_{b\to sV} = g_{b\to sV}\bar{s}\gamma_\mu(1-\gamma_5)b\, V^\mu$$

The $B \xrightarrow{V} (K, K^*)\bar{\chi}\chi$ amplitude is given in terms of the known form factors $f_+^{B\to K}(q^2)$, $A_{1,2}^{B\to K^*}(q^2)$, $V^{B\to K^*}(q^2)$ (lattice QCD etc).

- The explicit expressions for $d\Gamma(B \xrightarrow{V} (K, K^*)\bar{\chi}\chi)/dq^2$ are known and contain DM parameters M_V, m_χ, $g_{b\to sV}$, κ. May be extracted by a fit to the data.
- The ratio $d\Gamma(B \to K^*\bar{\chi}\chi)/d\Gamma(B \to K\bar{\chi}\chi)$ is not sensitive to DM parameters (cancel in the ratio), but sensitive to the mediator spin!

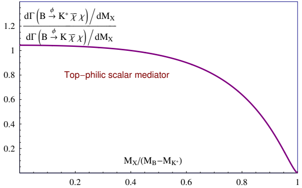
We therefore have two independent problems:

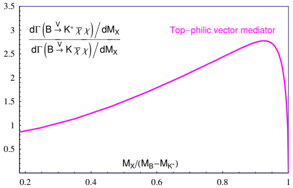
(i) Work out signatures for S and V scenarios

(ii) Determine the DM parameters for S and V by fits to the data.

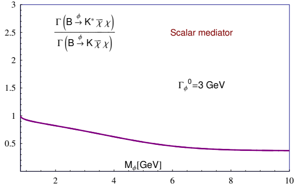
Signatures for S and V scenarios

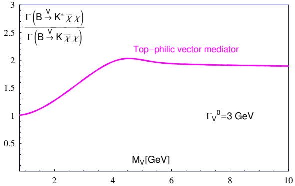
- $\hat{R}_{K^*/K}(q^2) = d\Gamma(B \to K^*\bar{\chi}\chi)/d\Gamma(B \to K\bar{\chi}\chi)$
(insensitive to DM parameters)





- $R_{K^*/K} = \Gamma(B \to K^*\bar{\chi}\chi)/\Gamma(B \to K\bar{\chi}\chi)$
(sensitive to the mediator mass M_R and width Γ_R^0)





A simple exercise: Constraints on $B \to K^* M_X$ assuming that excess in $B \to K M_X$ is due to $B \xrightarrow{R} K\chi\chi$.

$$\frac{\Gamma(B \to K^* M_X)}{\Gamma(B \to K^* \bar{\nu}\nu)_{\rm SM}} = \frac{\Gamma(B \to K^* \bar{\nu}\nu)_{\rm SM} + \Gamma(B \to K^* \bar{\chi}\chi)}{\Gamma(B \to K^* \bar{\nu}\nu)_{\rm SM}}$$

$$= 1 + \underbrace{\frac{\Gamma(B \to K^* \bar{\chi}\chi)}{\Gamma(B \to K \bar{\chi}\chi)}}_{\text{Calculated } R_{K^*/K}} \underbrace{\frac{\Gamma(B \to K \bar{\chi}\chi)}{\Gamma(B \to K \bar{\nu}\nu)_{\rm SM}}}_{\text{Belle: } 4.4\pm 1.5} \underbrace{\frac{\Gamma(B \to K \bar{\nu}\nu)_{\rm SM}}{\Gamma(B \to K^* \bar{\nu}\nu)_{\rm SM}}}_{\text{Theory:}(4.44\pm 0.30)/(9.8\pm 1.4)}$$

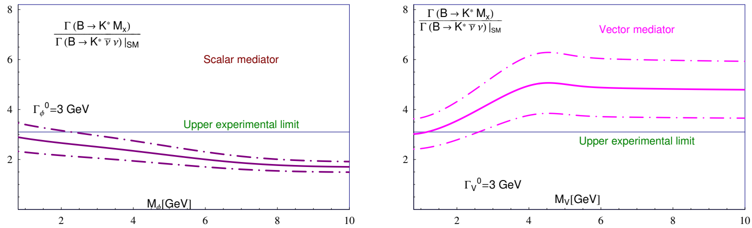
So, we obtain

$$\frac{Br(B \to K^* M_X)}{Br(B \to K^* \bar{\nu}\nu)_{\rm SM}} = 1 + (2 \pm 0.6) R_{K^*/K}$$

This expression may be combined with the Belle upper limit and the theory estimate $Br(B \to K^* \bar{\nu}\nu)_{\rm SM} = (9.8 \pm 1.4) \cdot 10^{-6}$

$$\frac{Br(B \to K^* M_X)}{Br(B \to K^* \bar{\nu}\nu)_{\rm SM}} < 3.1$$

Using these estimates, we obtain the following restrictions based on the integrated decay rates:

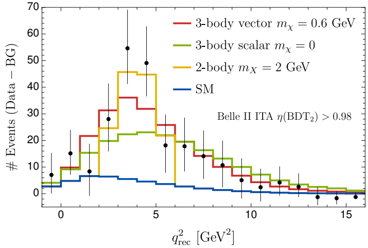


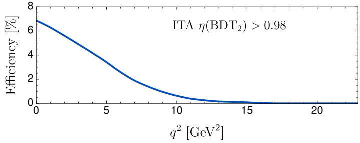
Obviously, within the S-scenario there are no restrictions on the mediator mass, whereas within the V-scenario only light mediator $M_V \leq 2-3$ GeV is allowed.

We take this into account when extracting the DM parameters by fitting the differential distribution in $B \to KM_X$.

Experimental data: $q^2 \to q^2_{rec}$, $d\Gamma_{exp}(B^+ \to K^+ M_X)/dq^2_{rec}$

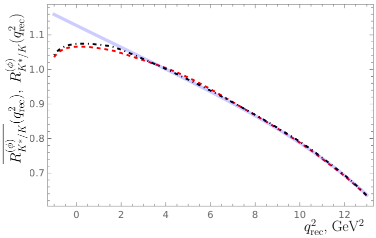
$$q^2 = (p_B - p_K)^2$$





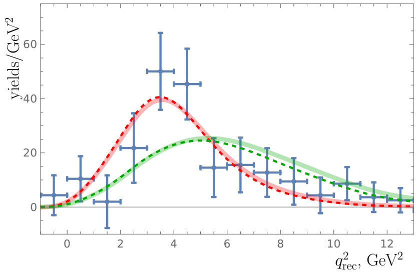
$$q^2_{rec} = E_B^2 + M_K^2 - 2E_B E_K$$
$$= q^2 + (E_B^2 - M_B^2) - 2\vec{p}_k(q^2)\cdot\vec{p}_B$$

Recalculate observables
$q^2 \to q^2_{\rm rec}$:

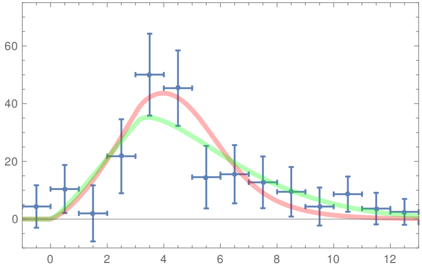


BELLE-II data fitted in S-scenario and V-scenario

S-scenario



V-scenario



S-scenario

$M_\phi = 2.4$ GeV, $\Gamma^0_\phi = 2.9$ GeV,
$m_\chi = 0.4$ GeV
$M_\phi = 20$ GeV, Γ^0_ϕ=20 GeV,
$m_\chi = 0.4$ GeV

V-scenario

$M_V = 3$ GeV, $\Gamma^0_V = 4$ GeV,
$m_\chi = 0.6$ GeV
$M_V = 20$ GeV, $\Gamma^0_V = 4$ GeV,
$m_\chi = 0.6$ GeV [excluded by data on $\Gamma(B \to K^*\nu\nu)$, previous slide]

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Summary-1

We studied conjectures that the observed excess in $B \to KM_X$ is due to the decay $B \xrightarrow{R} K\bar{\chi}\chi$ into two DM fermions $\bar{\chi}\chi$, with $R = \phi, V$. Our main findings are:

• S and V-scenarios yield qualitatively different ratios of the differential distribution of the excess events in $B \to K^* M_X$ and $B \to KM_X$ decays,

$$\hat{R}_{K^*/K}(q^2) = d\Gamma(B \to K^*\bar{\chi}\chi)/d\Gamma(B \to K\bar{\chi}\chi)$$

(which does not depend on DM parameters, but only on the mediator spin) and

$$R_{K^*/K} = \Gamma(B \to K^*\bar{\chi}\chi)/\Gamma(B \to K\bar{\chi}\chi).$$

Measuring $\hat{R}_{K^*/K}(q^2)$ and $R_{K^*/K}$ are excellent discriminators between these two scenarios.

• Both scenarios allow a good description of the shape of the observed excess events and an extraction of the corresponding DM parameters. In addition, making use of the constraints from the *integrated* rates restricts the possible mass of the vector mediator $M_V < 2 - 3$ GeV, whereas no constraints on the scalar mediator M_ϕ arise.

Summary-2

• The shape of $d\Gamma(B \to KM_X)/dq^2_{\rm rec}$ does not require a resonance $\sim$2 GeV (and presently cannot resolve such a resonance because of the procedures adopted in the Belle data analysis). May improve on a larger statistics.

• Within any top-philic mediator scenario one expects a similar excess in $B \to (\pi, \rho)M_X$ and $B \to (K, K^*)M_X$ decays relative to their SM values:

$$\frac{\Gamma(B \to \pi M_X)}{\Gamma(B \to \pi\bar{\nu}\nu)_{\rm SM}} \simeq \frac{\Gamma(B \to KM_X)}{\Gamma(B \to K\bar{\nu}\nu)_{\rm SM}}$$

and similar

$$\frac{\Gamma(B \to \rho M_X)}{\Gamma(B \to \rho\bar{\nu}\nu)_{\rm SM}} \simeq \frac{\Gamma(B \to K^* M_X)}{\Gamma(B \to K^*\bar{\nu}\nu)_{\rm SM}}.$$

[This happens because $\Gamma(B \to \pi\bar{\nu}\nu)_{\rm SM}$ and $\Gamma(B \xrightarrow{R} \pi\bar{\chi}\chi)$ are proportional to $V_{tb}V^*_{td}$ which cancel in the ratios. So the l.h.s and the r.h.s. of the ratios above are equal to each other up to SU(3)-breaking effects related to $s-$ and $d-quark$ differences.]

These features are crucial signatures of the top-philic DM scenarios.