Υ Decays Into Light Scalar Dark Matter

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Based on

G. K. Yeghiyan, Phys. Rev. D 80, 115019 (2009)

Υ meson: $b\bar{b}$, J=1

We consider

$$\Upsilon(1S) \to \Phi\Phi^*$$

$$\Upsilon(3S) \to \Phi\Phi^* \gamma$$

within the class of light (mass ~ few GeV or less) scalar DM models where these decays are due to exchange of heavy virtual states (with a mass $\gg M_\Upsilon$)

Other possibility that these decays are mediated by a light (preferably resonant) degree of freedom have been considered earlier:

Gunion, Hooper, McElrath, PRD 73, 015001 (2006):

P Fayet et al (in a number of papers).

GeV or lighter DM models: have in general tension with satisfying $\Omega_{DM}h^2 \sim 0.11$

may be avoided if DM annihilates due to exchange of light resonances (beyond the scope of the paper)

or, even if no light mediators, still may have no tension with $\Omega_{DM}h^2 \sim 0.11$ for spin-0 DM, e.g

- WIMPless miracle (J. Feng, J. Kumar, et al.) :
  within the MSSM with gauge mediated SUSY breaking,
  scalar DM particle in the hidden sector, or
- Type-II 2HDM with light scalar DM,
  if $v_2/v_1 = \tan\beta >> 1$, (Bird, Kowalewski, Pospelov)

Try to test this class of models, in particular using Υ decays with missing energy

Most recent experimental data - BaBaR:

$B_{exp}(\Upsilon(1S) \rightarrow \text{invisible}) < 3 \bullet 10^{-4}$

and

$B_{exp}(\Upsilon(3S) \rightarrow \gamma + \text{invisible}) < 3 \bullet 10^{-6}$ **for** $s^{1/2} \leq 7$ **GeV**

- **May constrain light spin-0 DM models even if no light propagators are exchanged in $\Upsilon(1S) \rightarrow \Phi\Phi^*$ and $\Upsilon(3S) \rightarrow \Phi\Phi^* \gamma$.**
- **Bounds are derived on the parameters which cannot be tested otherwise**

Problem: bound on $\Upsilon(3S) \rightarrow \gamma + \text{invisible}$ is derived assuming that the photon energy is monochromatic- may be used to make only preliminary estimates of possible constraints on light DM models with non-resonant DM production.

The approach:

integrate out heavy degrees of freedom, use low-energy effective theory of four-particle interactions:

$$H_{eff} = \frac{2}{\Lambda_H^2} \sum_i C_i \; O_i$$

$$O_1 = m_b \left(\bar{b}\; b\right)\left(\Phi^*\Phi\right), \qquad O_2 = i m_b \left(\bar{b}\gamma_5 b\right)\left(\Phi^*\Phi\right),$$

$$O_3 = \left(\bar{b}\gamma^\mu b\right)\left(\Phi^* i\overleftrightarrow{\partial}_\mu \Phi\right), \quad O_4 = \left(\bar{b}\gamma^\mu\gamma_5 b\right)\left(\Phi^* i\overleftrightarrow{\partial}_\mu \Phi\right)$$

$$\overleftrightarrow{\partial} = 1/2(\overrightarrow{\partial} - \overleftarrow{\partial})$$

- **The most general effective Hamiltonian to the LO in $1/m_b$ and $1/\Lambda_H$ expansions.**
- **One can perform model-independent analysis, then applying the derived results to particular models**

$$B(\Upsilon(1S) \to \Phi\Phi^*) = \frac{\Gamma(\Upsilon(1S) \to \Phi\Phi^*)}{\Gamma_{\Upsilon(1S)}} = \frac{C_3^2}{\Lambda_H^4} \frac{f_{\Upsilon(1S)}^2}{48\pi\Gamma_{\Upsilon(1S)}} \left[M_{\Upsilon(1S)}^2 - 4m_\Phi^2\right]^{3/2}$$

$$B(\Upsilon(1S) \to \Phi\Phi) = 0$$

if $\Phi = \Phi^*$ - may be inferred without any derivation

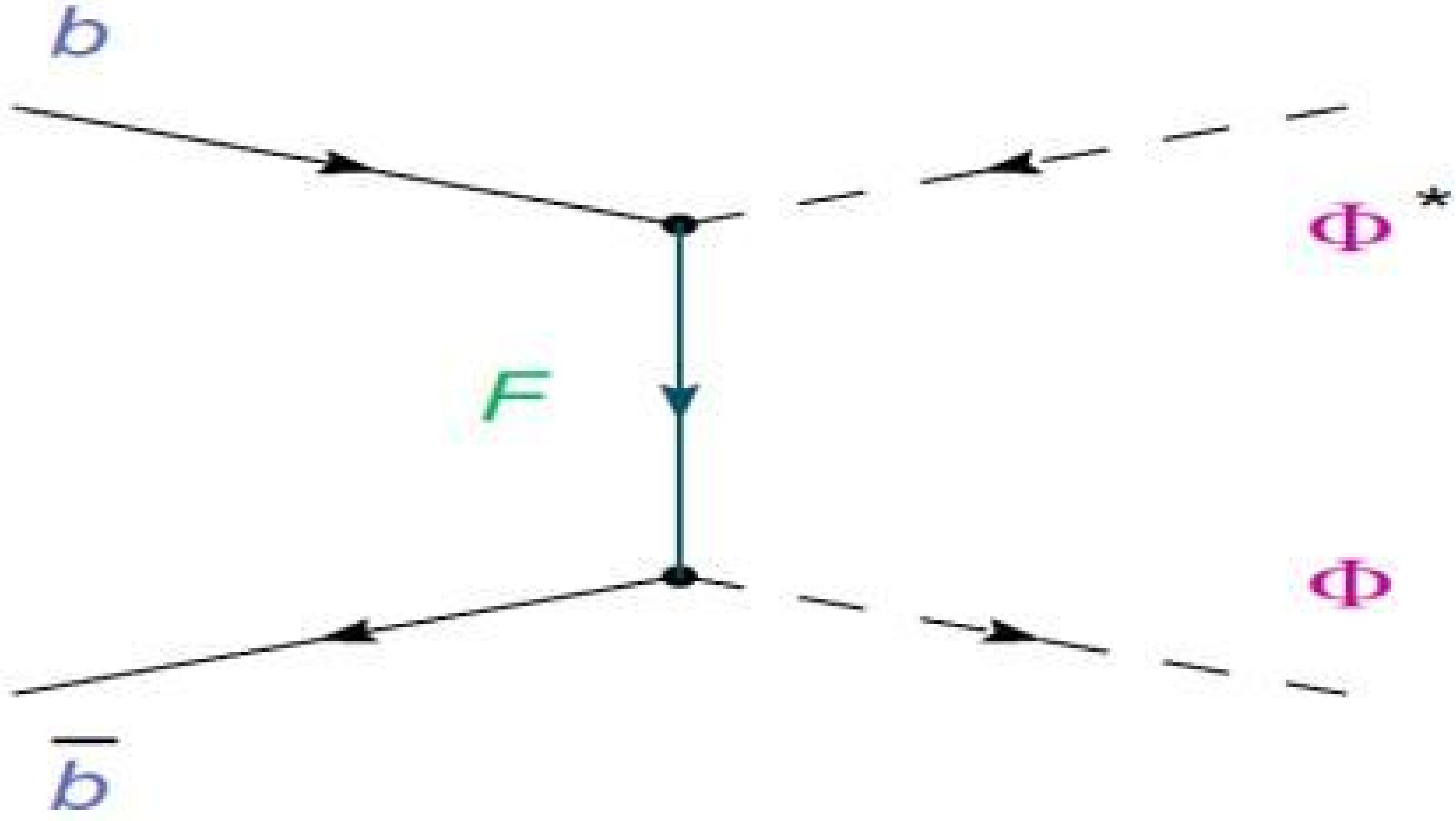
By angular momentum conservation:

$\Phi\ \Phi$ must be a P-wave state - impossible because of the Bose-Einstein symmetry of identical particles.

- **Signal for $\Upsilon \to$ invisible would mean that DM particle, if being a light scalar, has a complex field nature.**
- **No signal implies some constraints on the models with light complex spin-0 DM.**

$B_{exp}(\Upsilon(1S) \to \text{invisible}) < 3 \bullet 10^{-4}$ leads to

$$|C_3| < 0.75 \left(\frac{\Lambda_H}{100GeV}\right)^2 \left(1 - \frac{4m_\Phi^2}{M_{\Upsilon(1S)}^2}\right)^{-3/4}$$



Mirror Fermion Models

$$-\mathcal{L} = \Phi\ (\lambda_{b_L}\ \overline{F}_{b_R}\ b_L\ +\ \lambda_{b_R}\ \overline{F}_{b_L}\ b_R)\ +\ h.c.\ +\ \ldots$$

e.g. MSSM with gauge mediated SUSY breaking with DM in the hidden sector and F-s as connectors

Two scenarios are considered

- **Chiral scenario: e.g.** $\lambda_{bR} = 0$
- **Non – chiral scenario:** $\lambda_{bR} = \lambda_{bL} = \lambda_b$

$$- \mathcal{L} = \Phi \; (\lambda_{b_L} \; \overline{F}_{b_R} \, b_L \; + \; \lambda_{b_R} \; \overline{F}_{b_L} \, b_R) \; + \; h.c. \; + \; ...$$

Chiral scenario: e.g. $\lambda_{bR} = 0$

$B_{exp}(\Upsilon(1S) \to \Phi \, \Phi^{*}) < 3 \bullet 10^{-4}$ leads to

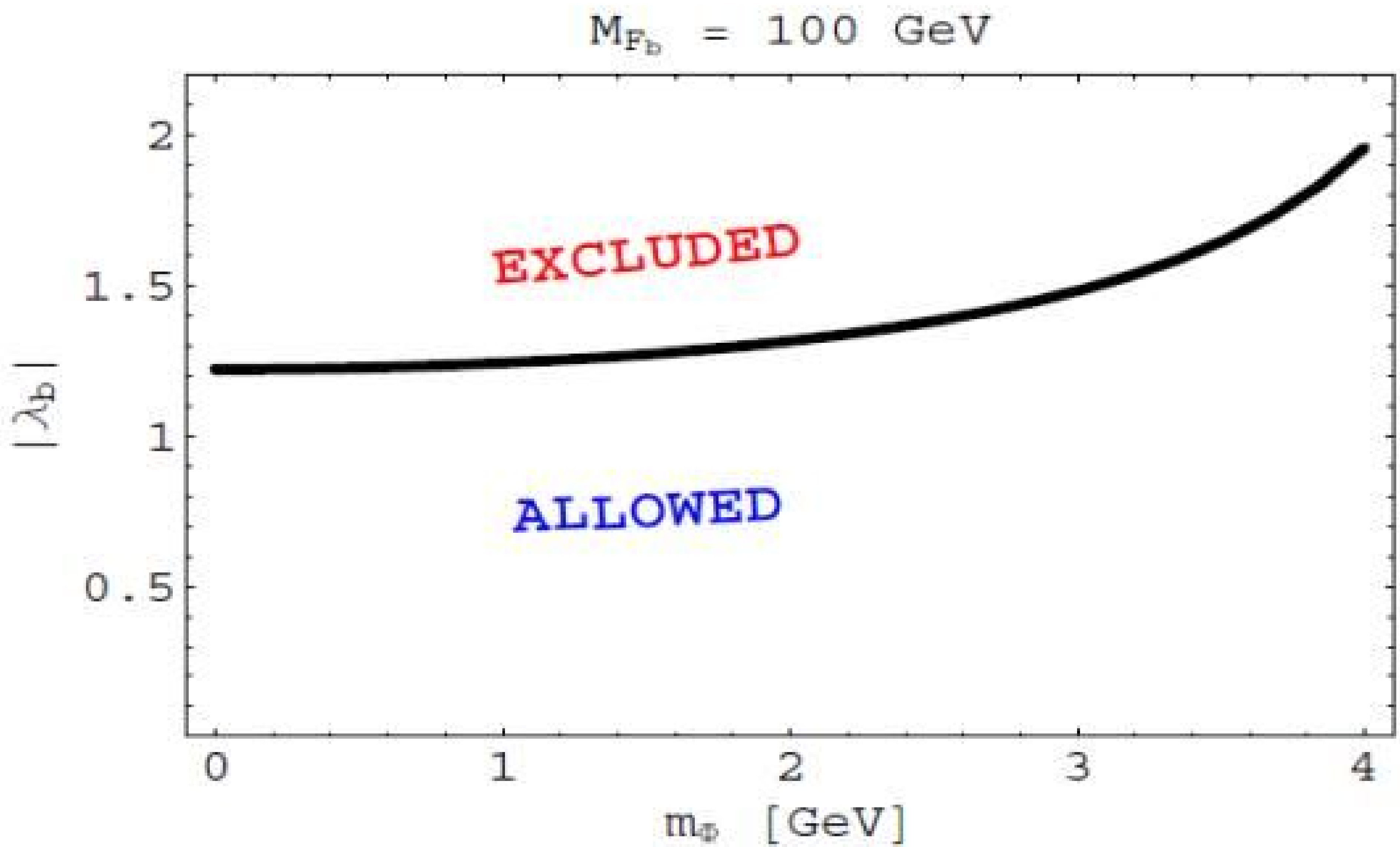
$$|\lambda_{b_L}| < 1.73 \left(\frac{M_{F_b}}{100GeV} \right) \left(1 - \frac{4m_{\Phi}^2}{M_{\Upsilon(1S)}^2} \right)^{-3/8}$$

Non – chiral scenario: $\lambda_{bR} = \lambda_{bL} = \lambda_b$

$$|\lambda_b| < 1.22 \left(\frac{M_{F_b}}{100GeV} \right) \left(1 - \frac{4m_{\Phi}^2}{M_{\Upsilon(1S)}^2} \right)^{-3/8}$$

$\lambda_{bR} = 0$: $$|\lambda_{b_L}| < 1.73 \left(\frac{M_{F_b}}{100GeV}\right) \left(1 - \frac{4m_\Phi^2}{M_{\Upsilon(1S)}^2}\right)^{-3/8}$$

$\lambda_{bR} = \lambda_{bL} = \lambda_b$ $$|\lambda_b| < 1.22 \left(\frac{M_{F_b}}{100GeV}\right) \left(1 - \frac{4m_\Phi^2}{M_{\Upsilon(1S)}^2}\right)^{-3/8}$$



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- **Bounds on λ_b – couplings are derived for the first time**
- **DM scattering off nuclei and/or annihilation lead to constraints on λ_u and λ_d but not λ_b**
- **$B \to K$ + invisible and $B_s \to$ invisible depend on λ_t or a combination of λ_b and λ_s but not on λ_b alone**
- **In other words, study of $\Upsilon(1S) \to \Phi\,\Phi^*$ leads to bound on parameters of the model that could not be constrained otherwise**

Non – chiral scenario: $\lambda_{bR} = \lambda_{bL} = \lambda_b$

$B_{exp}(\Upsilon(1S) \to \Phi\,\Phi^*) < 3 \bullet 10^{-4}$ **leads to**

$$|\lambda_b| < 1.22 \left(\frac{M_{F_b}}{100GeV}\right)\left(1 - \frac{4m_\Phi^2}{M_{\Upsilon(1S)}^2}\right)^{-3/8}$$

May be improved as $B(\Upsilon \to \Phi\,\Phi^*\,\gamma) \propto (M_{Fb}/m_b)^2$
Preliminary estimate from
$B_{exp}(\Upsilon(3S) \to \gamma + \text{invisible}) < 3 \bullet 10^{-6}$

$|\lambda_b| < 0.5$, $|\lambda_b| < 0.65$, $|\lambda_b| < 0.9$ **respectively for**

$M_{Fb} = 100$ GeV, $M_{Fb} = 200$ GeV, $M_{Fb} = 400$ GeV

One estimates also to have rigorous bounds from

$B(\Upsilon \to \Phi \Phi \gamma) \propto \tan^2 \beta$ on the parameters of

type-II 2HDM with light self-conjugate scalar DM.

Experimental studies of $\Upsilon \to \gamma$ + invisible for the photons with non-monochromatic energies are encouraged

Conclusions and Summary

- $\Upsilon(1S) \to \Phi\,\Phi^*$ and $\Upsilon(3S) \to \Phi\,\Phi^*\,\gamma$ have been studied within the models where DM production is due to exchange of heavy degrees of freedom.

- $B(\Upsilon(1S) \to \text{invisible}) < 3 \bullet 10^{-4}$ leads to constraints on the model parameters that cannot be tested by the other DM search experiments

- Bounds may also be derived from study of $\Upsilon \to \Phi\,\Phi^*\,\gamma$. We encourage experimental groups to analyze data for $\Upsilon \to \gamma + \text{invisible}$ for non-monochromatic photon energy as well.