Υ Decays Into Light Scalar Dark Matter

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QWG 2010, Fermilab

May 18-21, 2010

Based on

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

Objective:

To consider the possibility of using of spin-1 bottomonium decays with missing energy, to test the models with a GeV or lighter DM;

more precisely, to test the parameter space inaccessible or hardly accessible by other approaches based on

DM scattering off nuclei (DAMA, XENON, CDMS, CoGeNT experiments)

DM annihilation (PAMELA, HEAT experiments)

DM productions in B-meson decays with missing energy

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:

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

and

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

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

Problem: bound on $\Upsilon(3S) \to \gamma + \text{invisible}$ **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:

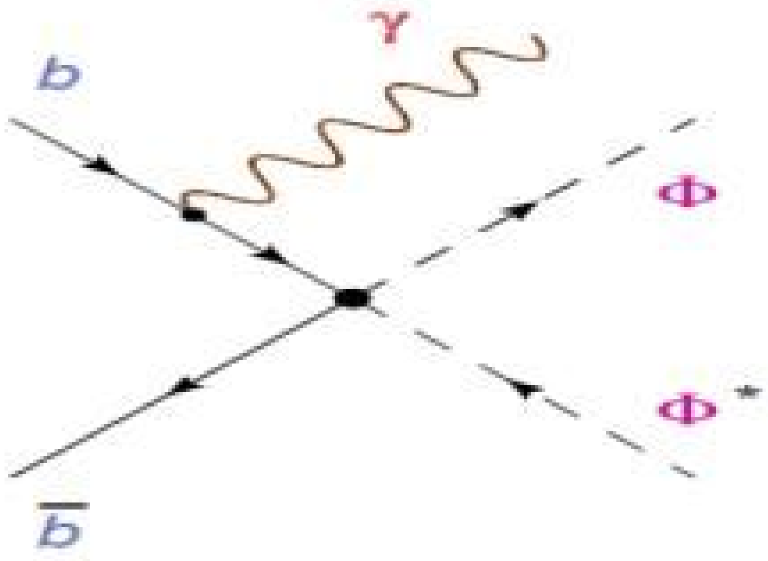
$$H_{eff} = \frac{2}{\Lambda_H^2} \sum_i C_i \, O_i$$

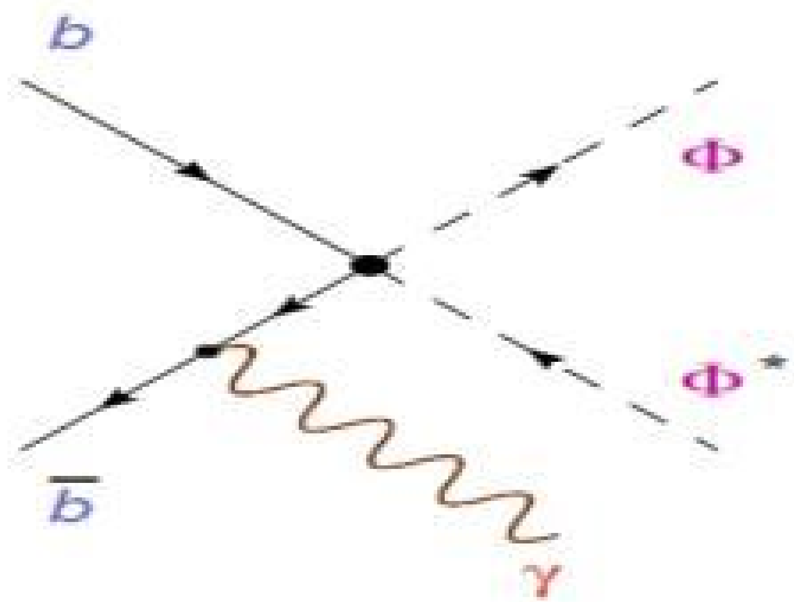
$$O_1 = m_b \left(\bar{b}\, b\right) \left(\Phi^* \Phi\right), \qquad O_2 = i m_b \left(\bar{b} \gamma_5 b\right) \left(\Phi^* \Phi\right),$$

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

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

- **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**





To the leading order of $1/\Lambda_H$ expansion $\Upsilon(3S) \to \Phi\Phi^*\gamma$ occurs by means of bi-local interactions

The local operator matrix elements are parameterized as

$$\langle 0|\ \bar{b}(0)b(0)\ |\Upsilon\rangle = \langle 0|\ \bar{b}(0)\gamma_5 b(0)\ |\Upsilon\rangle = \langle 0|\ \bar{b}(0)\gamma^\mu\gamma_5 b(0)\ |\Upsilon\rangle = 0$$

$$\langle 0|\ \bar{b}(0)\gamma^\mu b(0)\ |\Upsilon\rangle = f_\Upsilon M_\Upsilon \epsilon^\mu_\Upsilon(p), \quad \langle 0|\ \bar{b}(0)\sigma^{\mu\nu} b(0)\ |\Upsilon\rangle = -i f_\Upsilon\,[\ p^\mu, \epsilon^\nu_\Upsilon(p)\ ]$$

In the constituent quark approach the non-local hadronic operator matrix elements may be expressed as

$$\langle 0|\ \bar{b}(x_1)\ \Gamma\ b(x_2)\ |\Upsilon\rangle = e^{-i(p/2)\cdot(x_1+x_2)}\ \langle 0|\ \bar{b}(0)\ \Gamma\ b(0)\ |\Upsilon\rangle$$

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

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

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

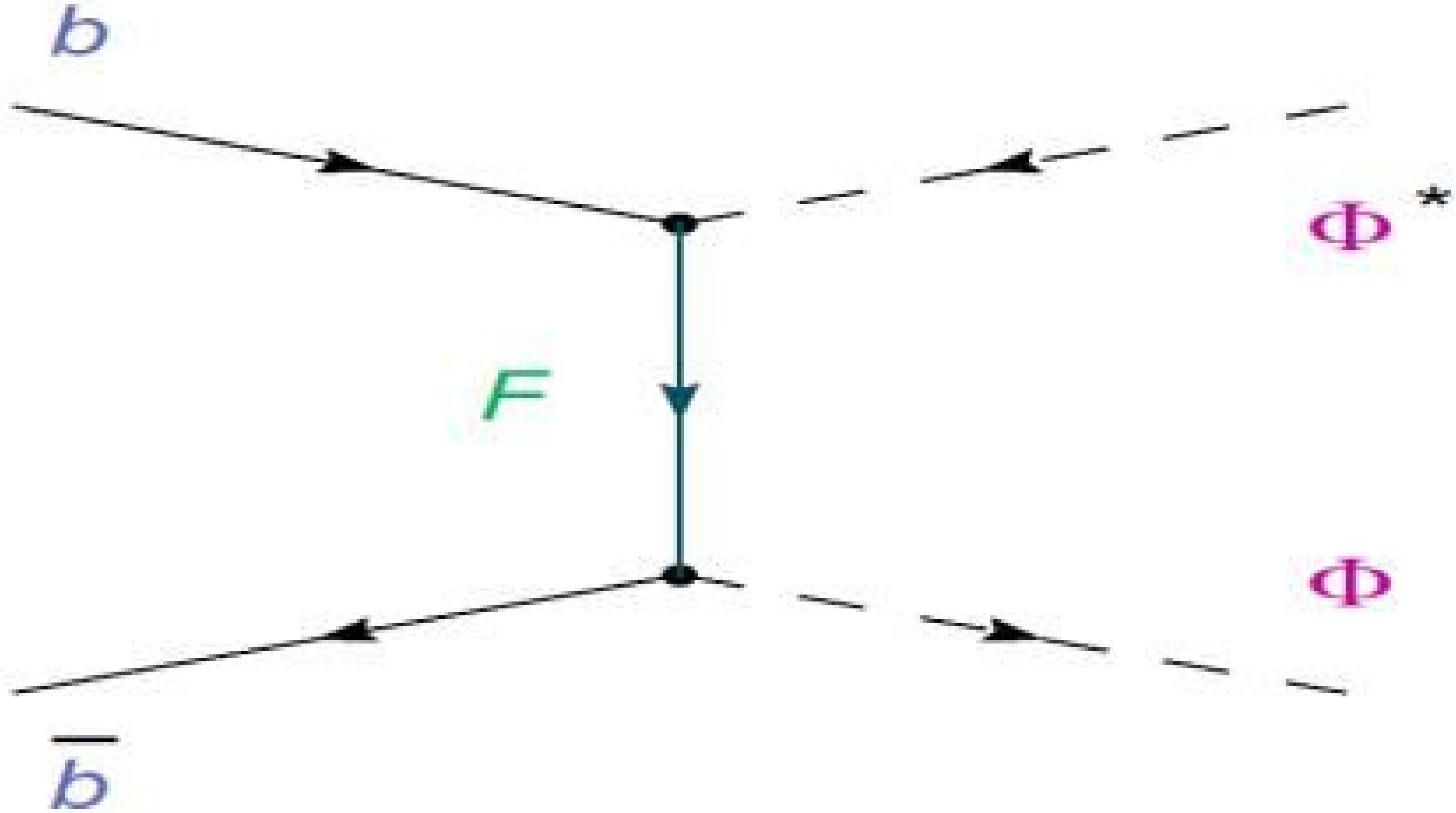
By angular momentum conservation:

Φ Φ 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

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

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:** $\lambda_{bR} = \lambda_{bL} = \lambda_b$

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

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

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

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

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

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

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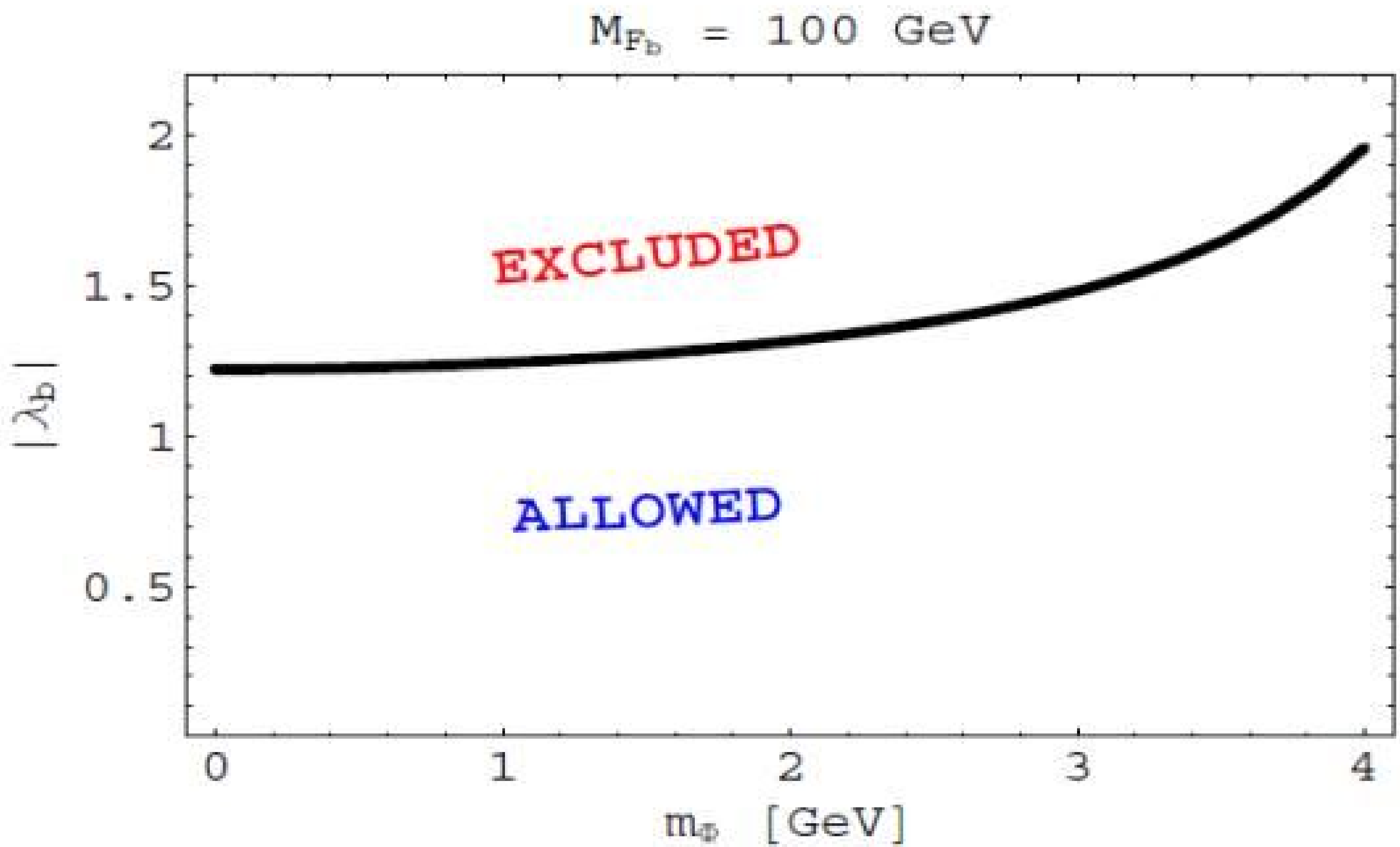

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- Bounds on λ_b – couplings are derived for the first time
- DM scattering off nuclei and/or annihilation lead to constraints on λ_u and λ_d but not λ_b
- $B \to K$ + invisible and $B_s \to$ invisible depend on λ_t or a combination of λ_b and λ_s but 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

The other mode, $\Upsilon(3S) \to \Phi\,\Phi^*\,\gamma$, is relevant both if $\Phi \neq \Phi^*$ and if $\Phi = \Phi^*$. But it is a capricious mode!

For simplicity, I present formula for BR for $\Phi = \Phi^*$ (qualitatively the analysis is true for $\Phi \neq \Phi^*$ as well).

For $\Phi = \Phi^*$

$$B(\Upsilon(3S) \to \Phi\Phi\gamma)_{|s<M^2_{\Upsilon(3S)}/2} = 2.6 \times 10^{-7}\left(C_1^2 + C_2^2\right)\left(\frac{100GeV}{\Lambda_H}\right)^4 f(x_\Phi)$$

$$f(x_\Phi) = \left(1 + \frac{4}{3}x_\Phi\right)\sqrt{1-8x_\Phi} - \frac{32}{3}x_\Phi(1-x_\Phi)\ln\left(\frac{1+\sqrt{1-8x_\Phi}}{2\sqrt{2}\sqrt{x_\Phi}}\right)$$

$$x_\Phi = m_\Phi^2/M^2_{\Upsilon(3S)}$$

Recall that $B_{exp}(\Upsilon(3S) \to \gamma + \text{invisible}) < 3 \bullet 10^{-6}$

In many models $B(\Upsilon(3S) \to \Phi\,\Phi^*\,\gamma)$ is far below the reach of experimental sensitivity (for $C_i \lesssim 1$)

In many models $B(\Upsilon(3S) \to \Phi\,\Phi^*\,\gamma)$ is far below the reach of experimental sensitivity

E.g. in the Minimal Scalar DM Model

(SM + self-conjugate scalar gauge singlet odd under Z_2)

Also, in mirror fermion models (with $\Phi \neq \Phi^*$),

chiral scenario $\lambda_{bR} = 0$:

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

Leads to *a phenomenological upper bound* on

$B(\Upsilon(3S) \to \Phi\,\Phi^*\,\gamma) < 1.57 \bullet 10^{-7}$

Compare to the BaBaR limit

$B_{exp}(\Upsilon(3S) \to \gamma + \text{invisible}) < 3 \bullet 10^{-6}$

On the other hand, in some models,

$C_{1,2} \propto$ heavy-to-light fermion mass ratio $\gg 1$

or

$C_{1,2} \propto \tan\beta \gg 1$ in large $\tan\beta$ scenario

Then one may have

$B(\Upsilon(3S) \to \Phi\, \Phi^{*} \gamma) \sim 10^{-5} - 10^{-4}$

⇒ One may have constraints on the model parameters!

Mirror fermion models,
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.

So, it is not simple… but one can get constraints on the light spin-0 DM model parameters when studying $\Upsilon \to \Phi\,\Phi^*\,\gamma$ decay

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 light 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 light DM 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.

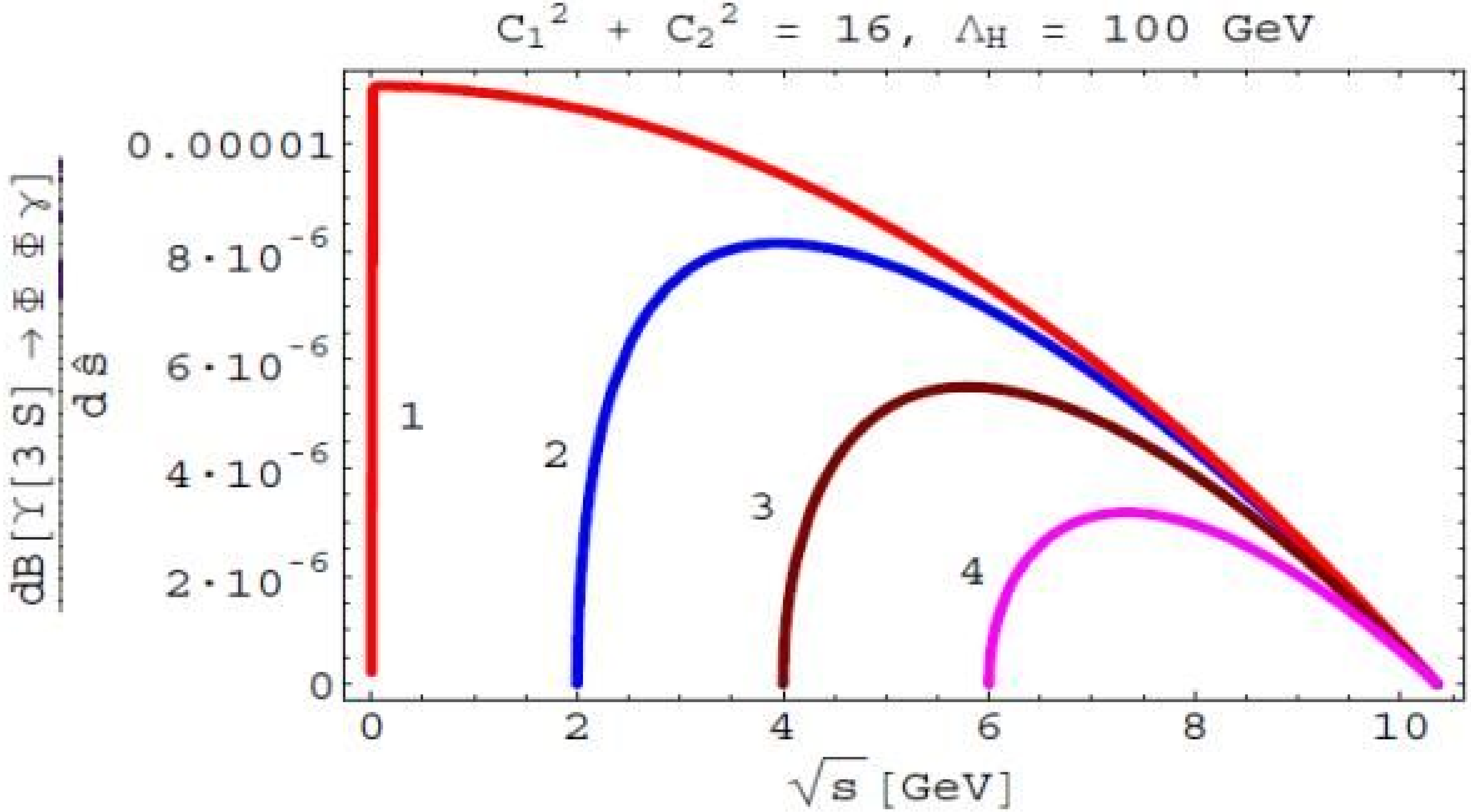

FIG. 3: The differential branching ratio $dB(\Upsilon(3S) \to \Phi\Phi\gamma)/d\hat{s}$ versus the missing mass $\sqrt{s}$ within a self-conjugate DM scenario for $m_\Phi = 1\ MeV$ (line 1), $m_\Phi = 1\ GeV$ (line 2), $m_\Phi = 2\ GeV$ (line 3) and $m_\Phi = 3\ GeV$ (line 4).

$$\frac{dB}{d\hat{s}}(\Upsilon(3S) \to \Phi\Phi\gamma) = \frac{(C_1^2 + C_2^2)}{\Lambda_H^4}\frac{\alpha}{4\pi}\frac{f_{\Upsilon(3S)}^2 M_{\Upsilon(3S)}^3(1-\hat{s})}{27\pi\Gamma_{\Upsilon(3S)}}\sqrt{\frac{\hat{s} - 4x_\Phi}{\hat{s}}}$$