Υ Decays Into Scalar Dark Matter

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Υ meson: $b\bar{b}$, J=1

Motivation:

An attempt to test the models with light DM ($m_\Phi \sim$ few GeV or less) by means of DM direct search in heavy meson decays.

May be complimentary to

DM direct search at colliders

DM direct search using DM scattering off nuclei (CDMS, XENON) – has poor sensitivity to GeV DM mass range.

The idea of exploiting Υ decays with missing energy is not new:

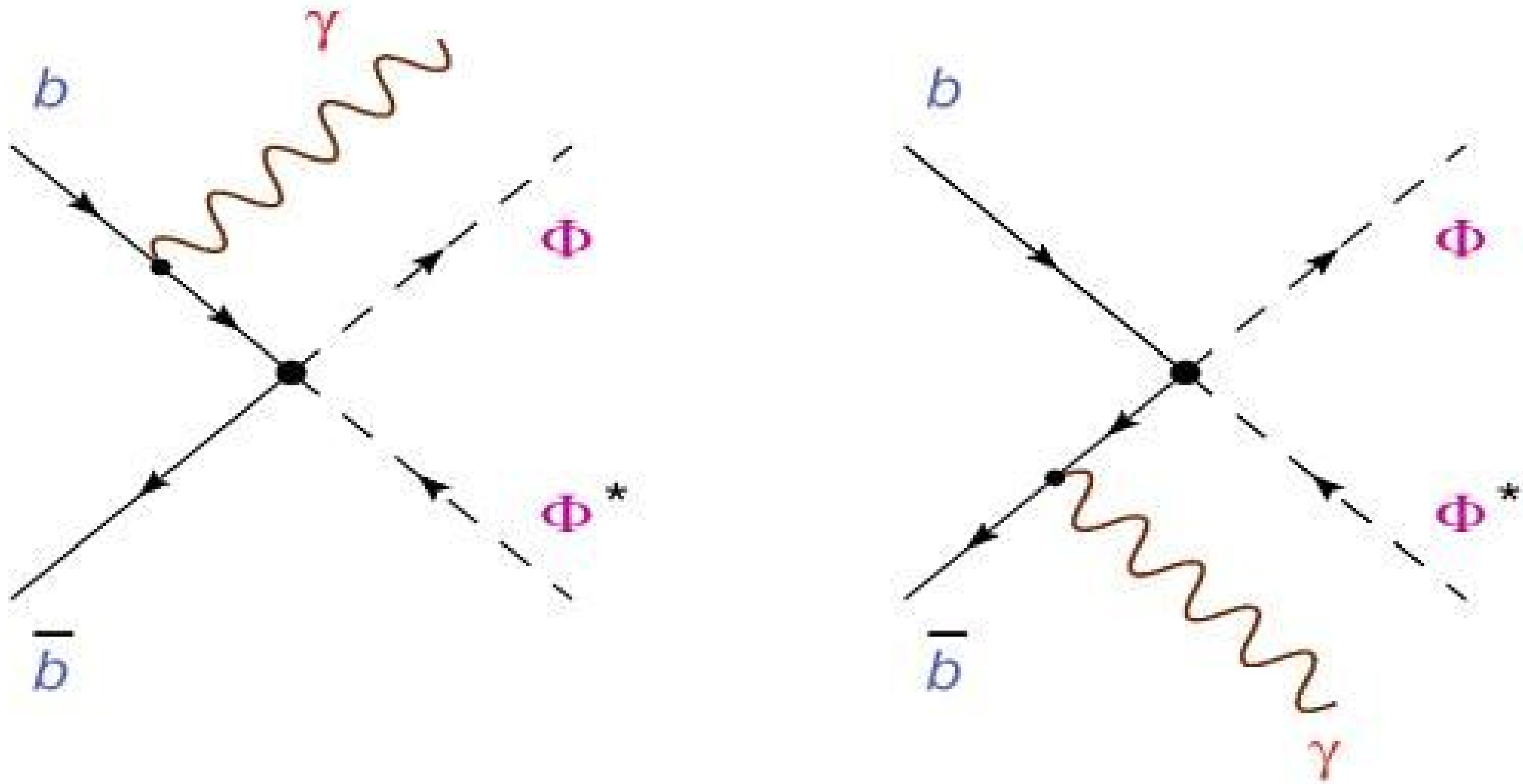
Gunion, Hooper, McElrath, PRD 73, 015001 (2006):

$\Upsilon \to \chi\chi\,\gamma$

in the NMSSM with a light ~ few GeV CP-odd Higgs

P Fayet:

$\Upsilon \to$ **light virtual gauge U boson** $\to \Phi\Phi^*$ **or** $\chi\chi$



Here we consider the class of scalar DM models where

$\Upsilon \to$ heavy ($\geq$ 100 GeV) virtual states $\to \Phi\Phi^*$

$\Upsilon \to$ heavy virtual states + $\gamma \to \Phi\Phi^*\gamma$

May be described by low-energy effective theory, integrating out heavy degrees of freedom

To the leading order in $1/m_b$ expansion, the most general H_{eff} is

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

where Λ_H is the heavy mass and

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

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

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

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The strategy of the analysis:

1. **Derive model-independent formulae for BR-s.**
2. **Confront with the experimental data, derive model-independent bounds on C_i**
3. **Translate these bounds into those onto the scalar DM models parameters.**

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Note that if $\Phi = \Phi^*$ then

$$\left\langle \Phi(p_1) \Phi(p_2) \middle| \Phi \, i \overleftrightarrow{\partial}_\mu \Phi \middle| 0 \right\rangle = 0$$

Only O_1 and O_2 contribute, if $\Phi = \Phi^*$

Consider

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

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

Why $\Upsilon(1S)$ and $\Upsilon(3S)$?

Belle: $B_{exp}(\Upsilon(1S) \to \text{invisible}) < 2.5 \bullet 10^{-3}$ **but there is no bounds on** $\Upsilon(nS) \to \text{invisible}, n = 2,3,4,5$

CLEO: $B_{exp}(\Upsilon(1S) \to \gamma + \text{invisible}) < 3 \bullet 10^{-5}$

$B_{exp}(\Upsilon(2S) \to \gamma + \text{invisible}) < 1.95 \bullet 10^{-4}$

BaBaR, preliminary:

$B_{exp}(\Upsilon(3S) \to \gamma + \text{invisible}) < (0.7 \div 31) \bullet 10^{-6}$ **– the strongest bound**

BaBaR Collaboration arXiv:0808.0017[hep-ex]

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

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

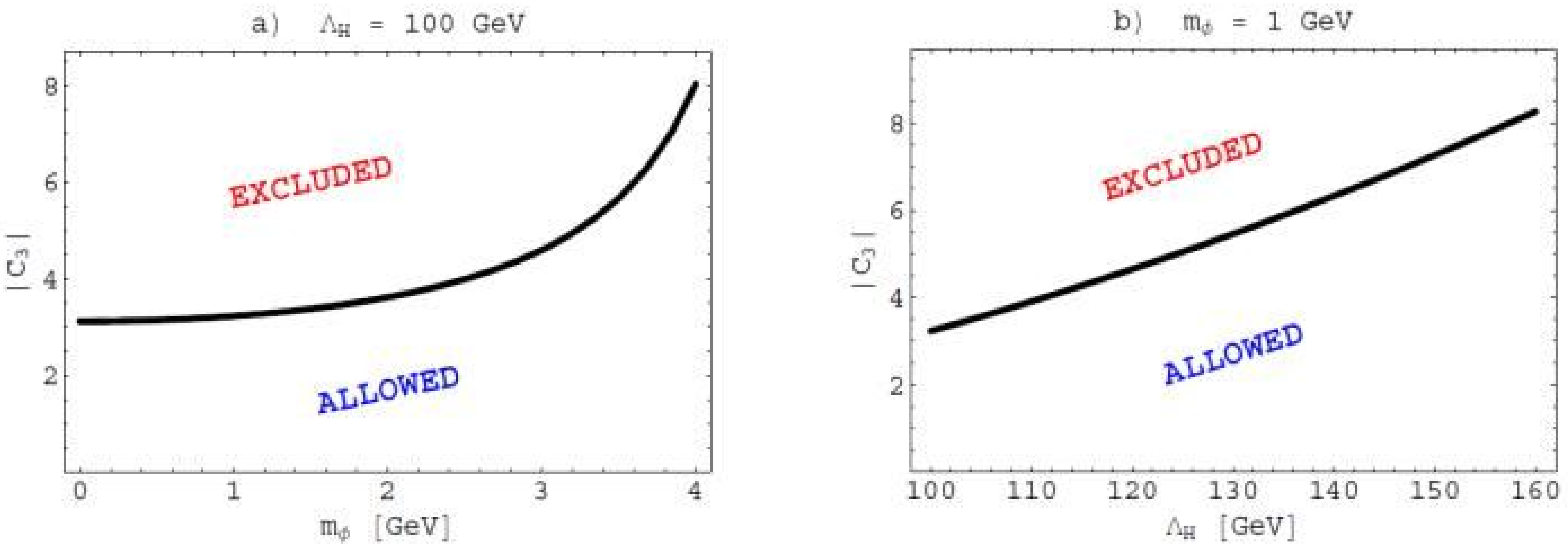
Signal for Y → invisible would mean that DM particle, if being a light scalar, has a complex field nature.

Inverse is not true: e. g.

B_{exp}(Y(1S) → invisible) < $2.5 \bullet 10^{-3}$ leads to

$$|C_3| < 3.12 \left(\frac{\Lambda_H}{100GeV}\right)^2 \left(1 - \frac{4m_\Phi^2}{M_{\Upsilon(1S)}^2}\right)^{-3/4}$$

We do not know any complex scalar DM model that would not comply or be essentially constrained by this bound



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$\Upsilon(3S) \rightarrow \Phi\Phi^{*}\gamma$: the case of $\Phi = \Phi^{*}$

$$B(\Upsilon(3S) \to \Phi\Phi\gamma) = \frac{(C_1^2 + C_2^2)}{\Lambda_H^4}\frac{\alpha}{4\pi}\frac{f^2_{\Upsilon(3S)}}{54\pi\Gamma_{\Upsilon(3S)}}\left[\left(M^2_{\Upsilon(3S)} + 2m^2_{\Phi}\right)\sqrt{M^2_{\Upsilon(3S)} - 4m^2_{\phi}} - \right.$$
$$\left. - \frac{8m^2_{\Phi}\left(M^2_{\Upsilon(3S)} - m^2_{\Phi}\right)}{M_{\Upsilon(3S)}} \ln\left(\frac{M_{\Upsilon(3S)} + \sqrt{M^2_{\Upsilon(3S)} - 4m^2_{\Phi}}}{2m_{\Phi}}\right)\right]$$

From BaBaR preliminaries: $B_{exp} < 3 \bullet 10^{-6}$ - yields

$$\sqrt{C_1^2 + C_2^2} < 4.16\left(\frac{\Lambda_H}{100\,GeV}\right)^2 f(m_{\Phi})$$

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$$\left. - \frac{8m_\Phi^2 \left(M_{\Upsilon(3S)}^2 - m_\Phi^2 \right)}{M_{\Upsilon(3S)}} \ln \left(\frac{M_{\Upsilon(3S)} + \sqrt{M_{\Upsilon(3S)}^2 - 4m_\Phi^2}}{2m_\Phi} \right) \right]$$

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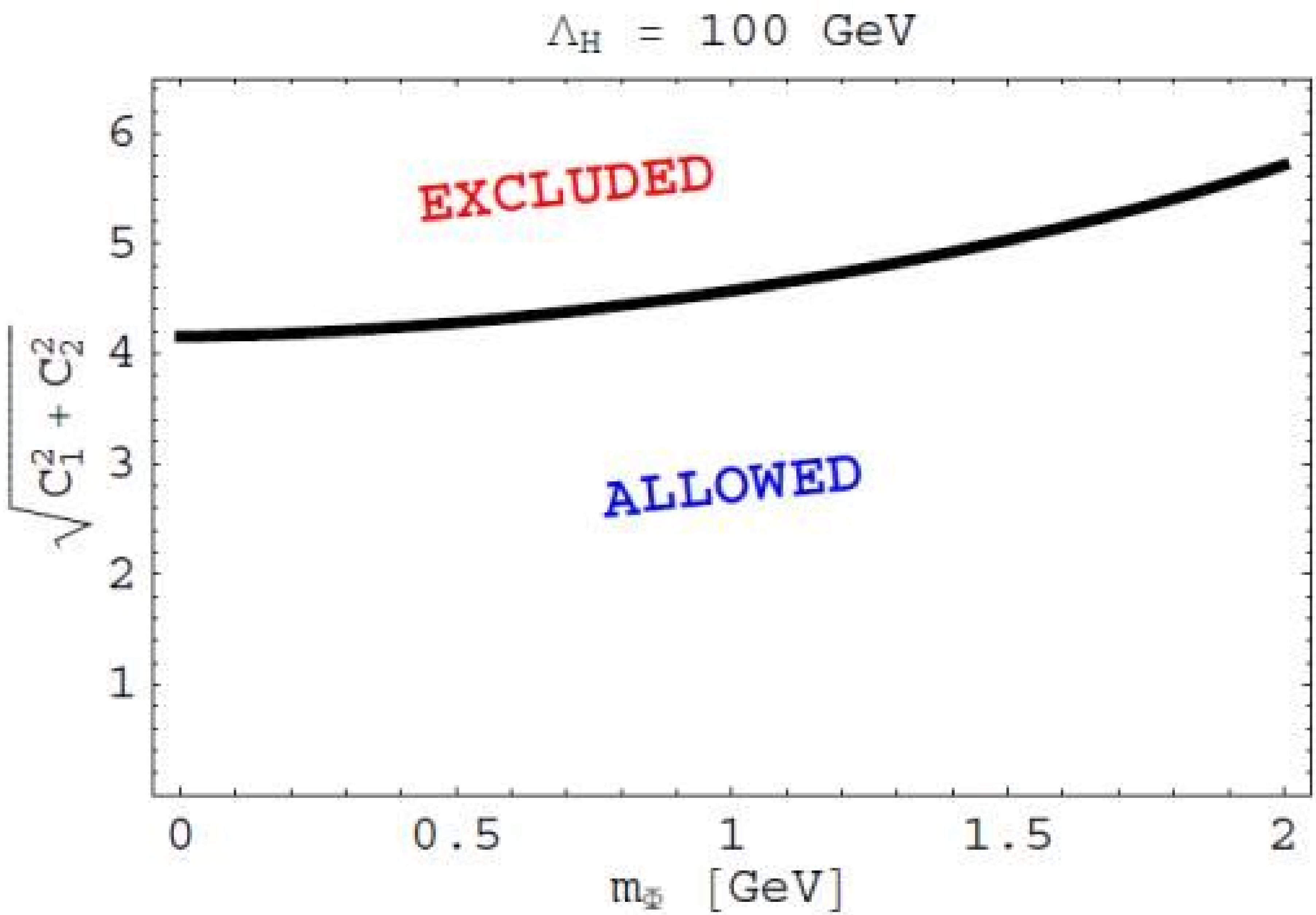
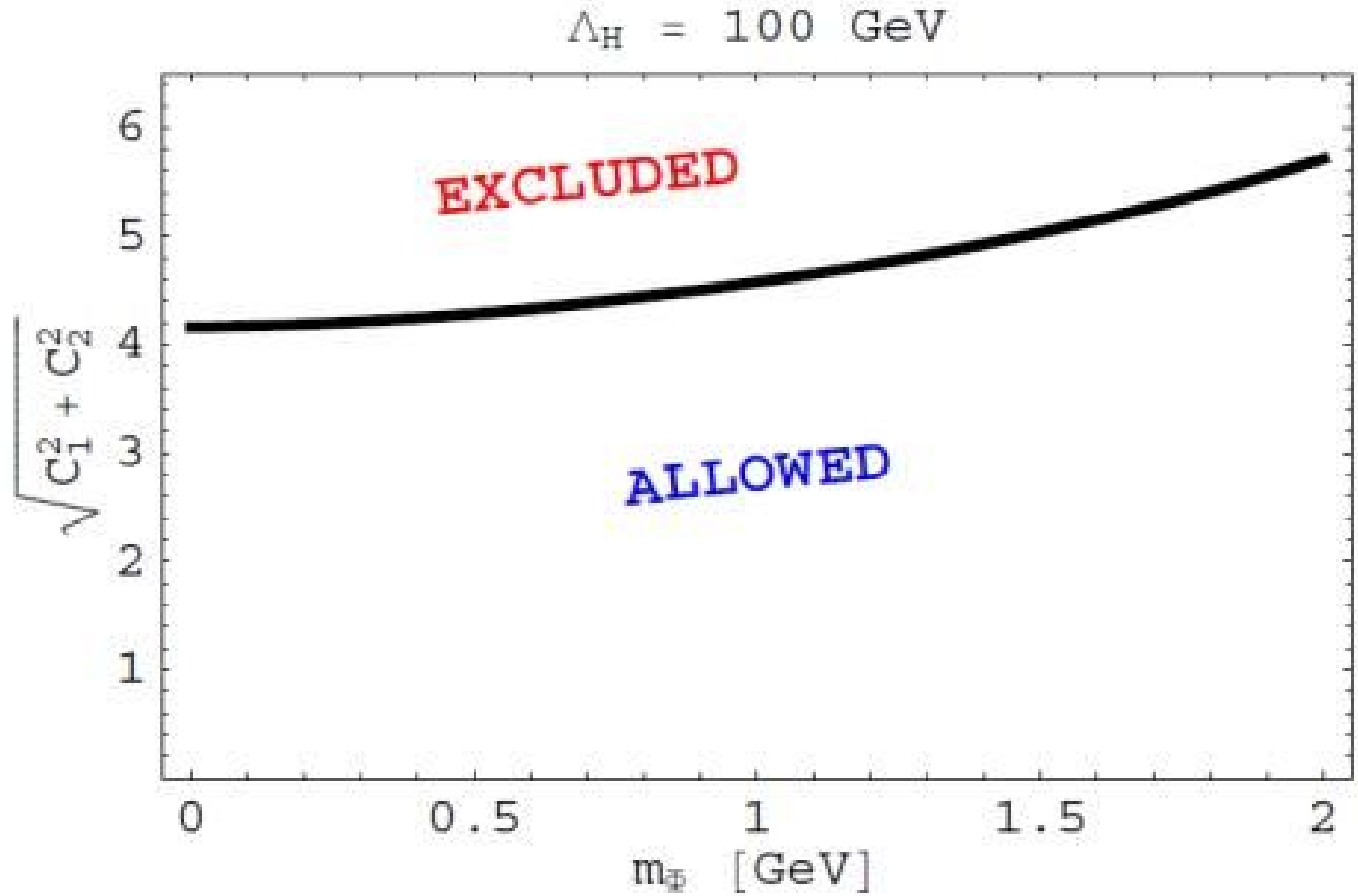
$$f(m_\Phi) = M_{\Upsilon(3S)}^{3/2} \left[\left(M_{\Upsilon(3S)}^2 + 2m_\Phi^2 \right) \sqrt{M_{\Upsilon(3S)}^2 - 4m_\Phi^2} - \right.$$
$$\left. - \frac{8m_\Phi^2 \left(M_{\Upsilon(3S)}^2 - m_\Phi^2 \right)}{M_{\Upsilon(3S)}} \ln \left(\frac{M_{\Upsilon(3S)} + \sqrt{M_{\Upsilon(3S)}^2 - 4m_\Phi^2}}{2m_\Phi} \right) \right]^{-1/2}$$

B(Υ(3S) → γ + invisible) < 3 • 10⁻⁶

$$\sqrt{C_1^2 + C_2^2} < 4.16\left(\frac{\Lambda_H}{100\,GeV}\right)^2 f(m_\Phi)$$





Too weak bound?

No, if e.g. C_1 or C_2 ∞ tan β >> 1 or ∞ M_F/m_b >> 1

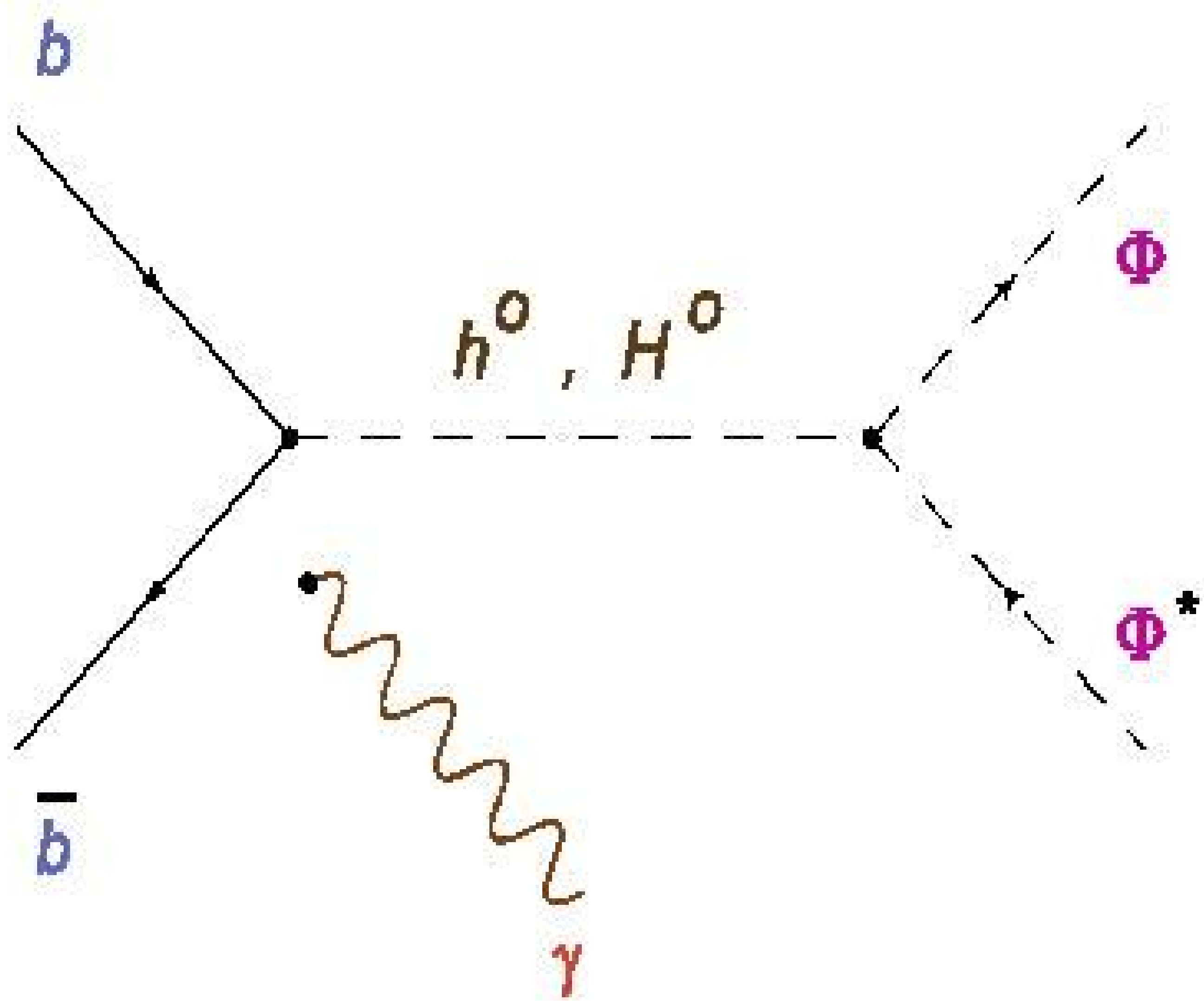
Then C_1 >> 1 or C_2 >> 1 - bound is actual!

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

Type II 2HDM with a scalar DM

$$-\mathcal{L} = \frac{m_0^2}{2}\Phi^2 + \lambda_1 \Phi^2 |H_1|^2 + \lambda_2 \Phi^2 |H_2|^2 + \lambda_3 \left(H_1 H_2 + h.c\right)$$

Υ **(3S) → (virtual) h^0, H^0 + γ → Φ Φ γ**



Type II 2HDM with a scalar DM

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Υ **(3S) → (virtual) h^0, H^0 + γ → $\Phi\,\Phi\,\gamma$**

Consider tan β >> 1

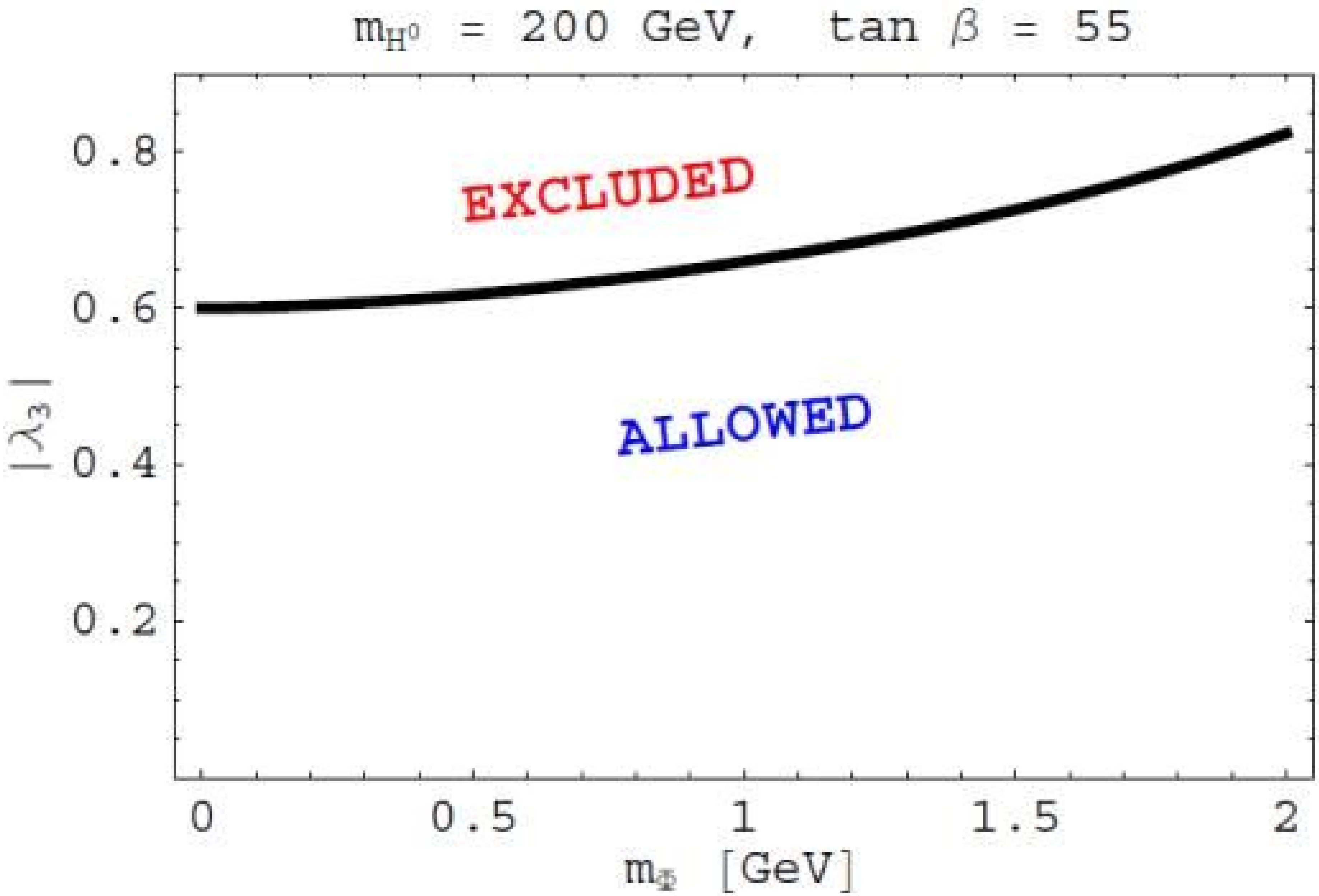
If the exchanged h^0 or H^0 is an NP-like Higgs, then

$$C_1 = \frac{-\lambda_3 \tan\beta}{2}\,, \qquad C_2 = 0$$

Get bounds on $|\lambda_3|$ for different choices of the Higgs mass and tan β

If the NP Higgs is H^0

$$\Lambda_H = m_{H^0}$$



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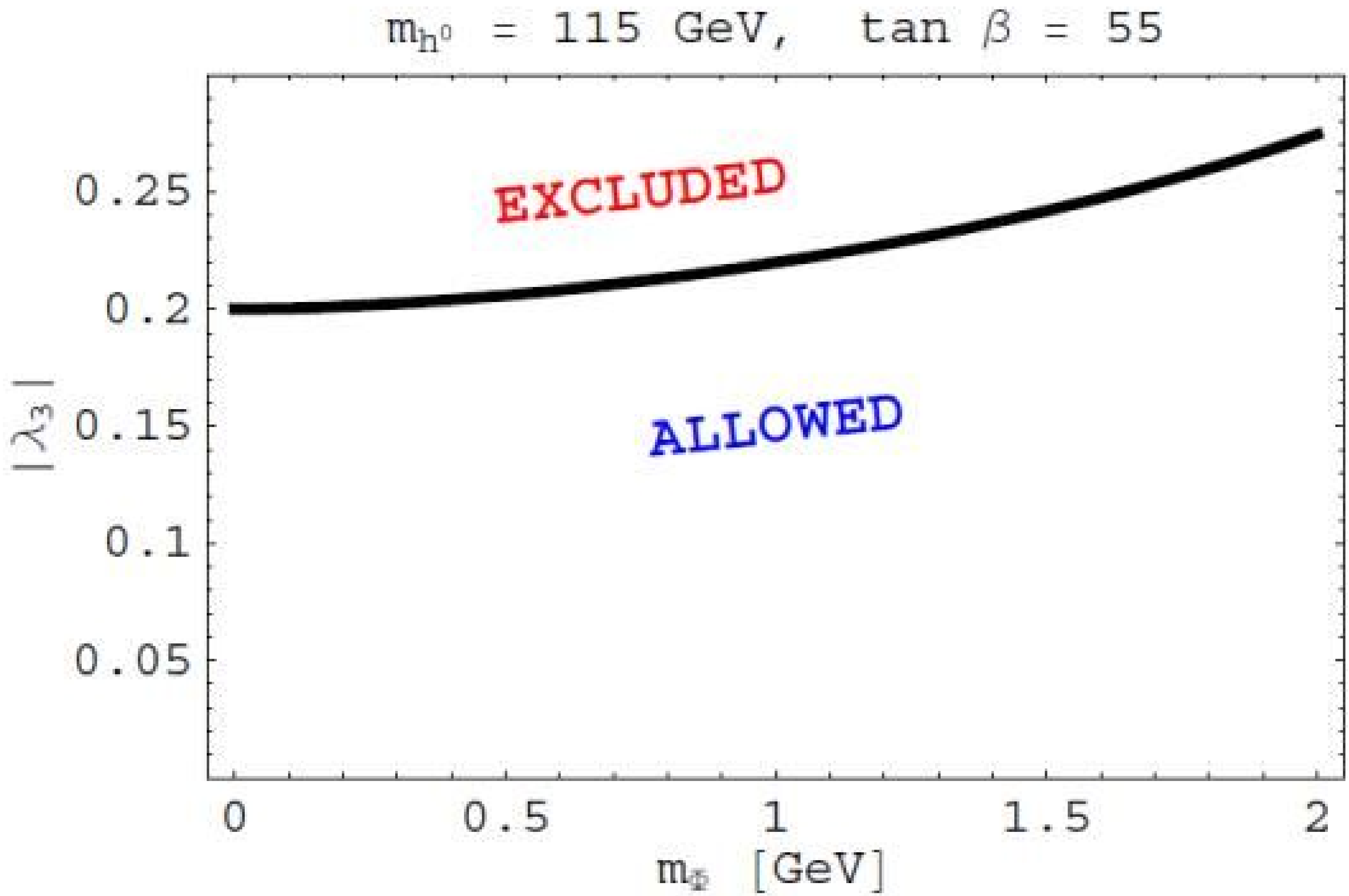
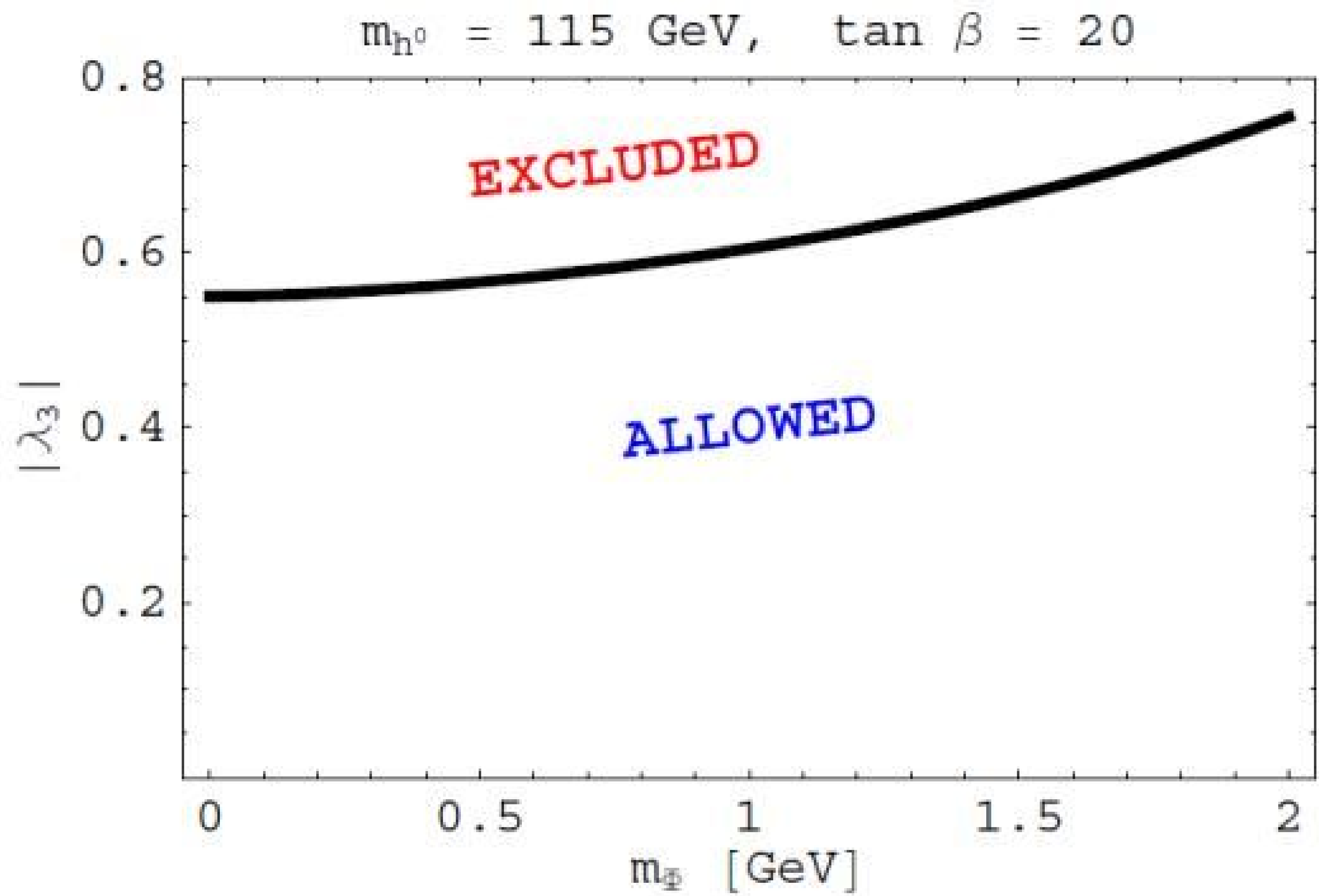


If the NP Higgs is h^0 $\Lambda_H = m_{h^0}$



Compare to other sources of constraints

$$-\mathcal{L} = \frac{m_0^2}{2}\Phi^2 + \lambda_1 \Phi^2 |H_1|^2 + \lambda_2 \Phi^2 |H_2|^2 + \lambda_3 (H_1 H_2 + h.c)$$

Υ (3S) $\rightarrow \Phi\,\Phi\,\gamma$: constraints on λ_3

b $\rightarrow$ s + invisible: constraints on λ_1, λ_2

(Bird, Kowalewski, Pospelov, MPA 21, 457 (2006)
Bird, Jackson, Kowalewski, Pospelov, PRL 93, 201803 (2004))

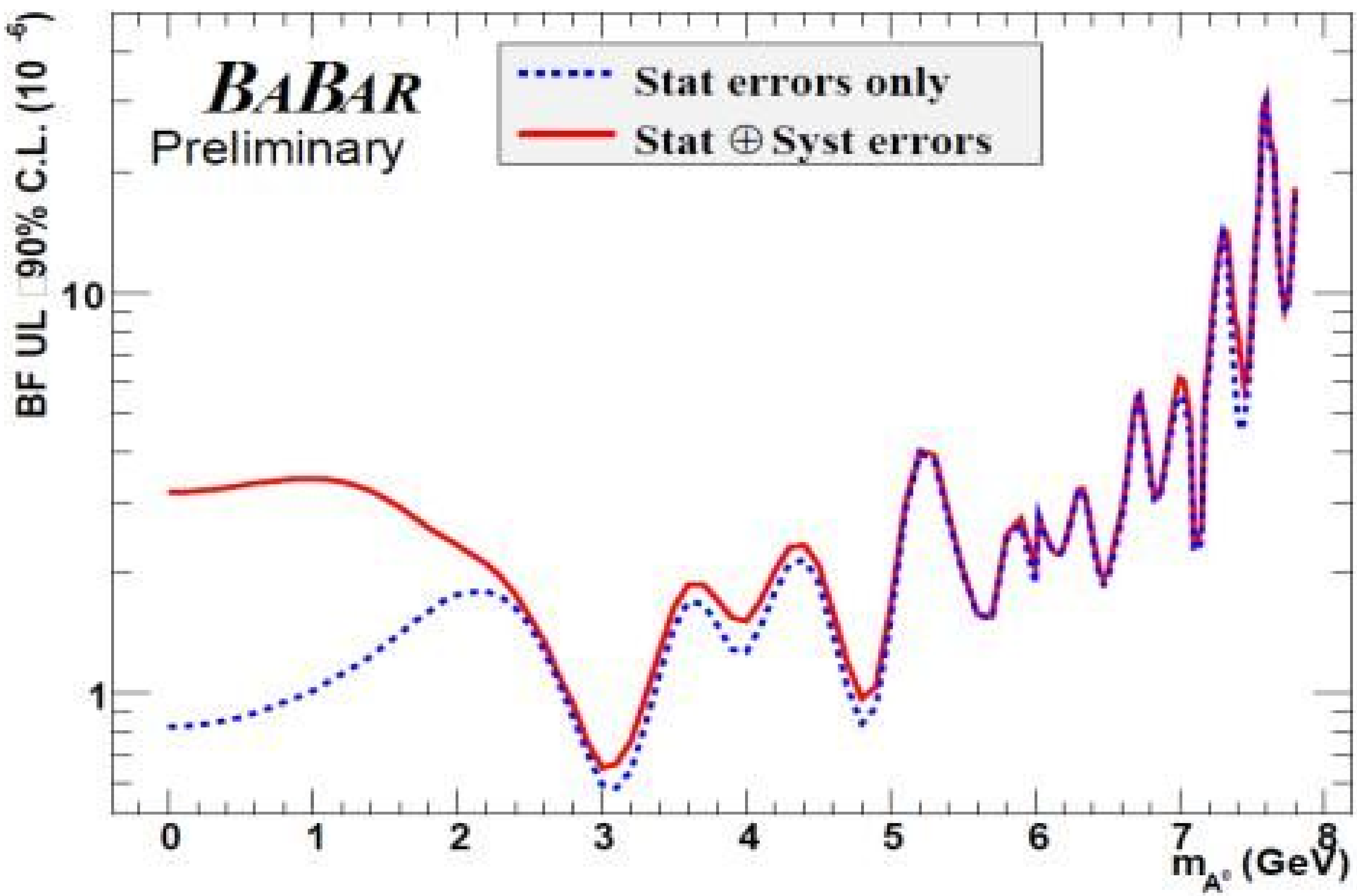
no constraints on λ_3 !

Nor one gets bounds on λ_3 from DM relic abundance constraints

Y(3S) $\rightarrow \Phi\,\Phi\,\gamma$ - in 2HDM with DM tests the regions of parameter space inaccessible for other sources of constraints

Conclusions and Summary

- $\Upsilon(1S) \to \Phi\,\Phi^*$ and $\Upsilon(3S) \to \Phi\,\Phi^*\,\gamma$ have been studied
- Model independent expressions for decays branching ratios have been derived
- Confronting theoretical results with the experimental data leads to constraints on light scalar DM models parameters if formulae for the decays BR-s have some enhancement factor



$B(\Upsilon \rightarrow A^0\,\gamma)$ x $B(\Upsilon \rightarrow A^0\,\gamma \rightarrow \gamma + \text{invisible}) < (0.7 \div 31) \bullet 10^{-6}$

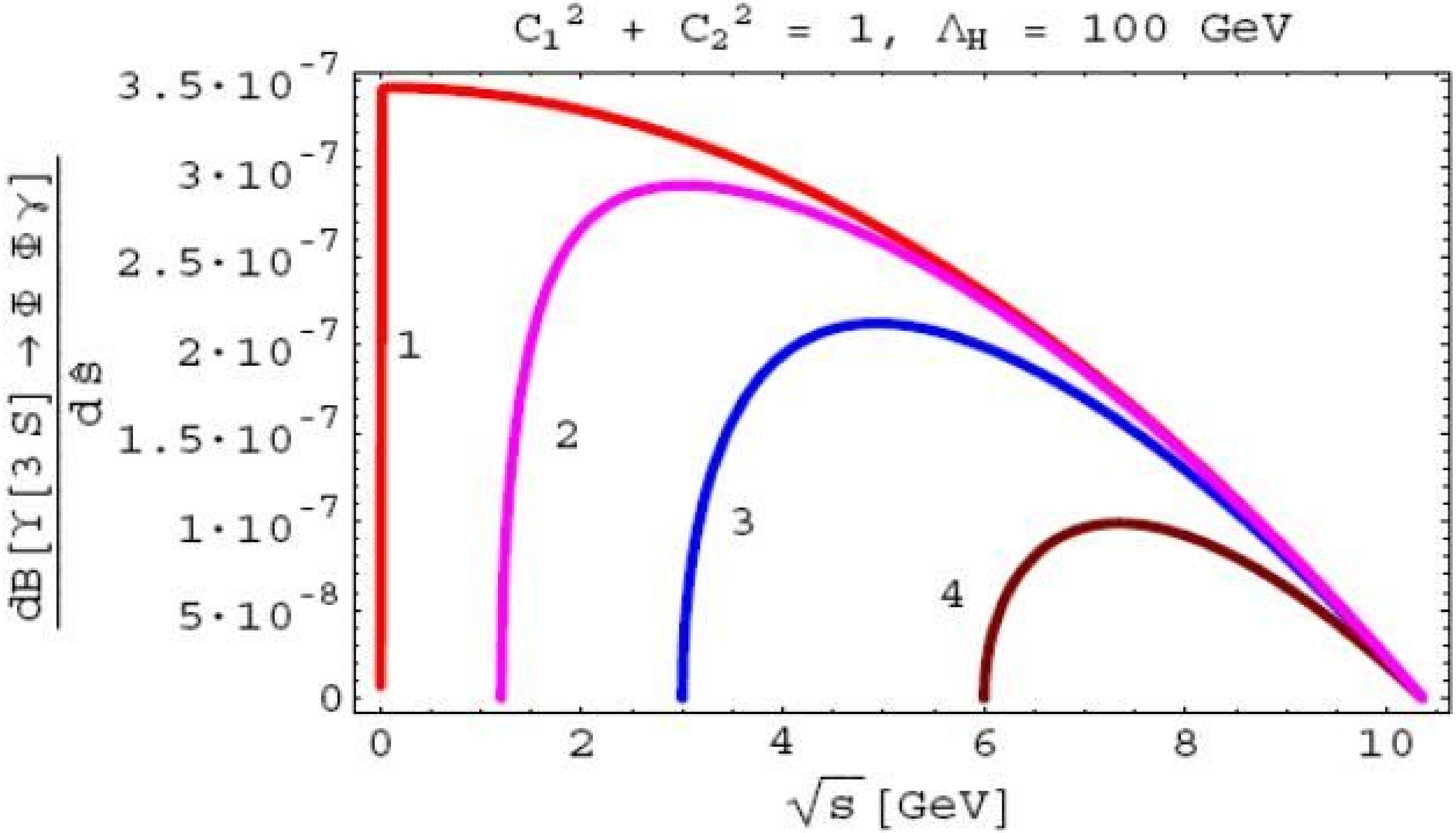
We hope that final results will be for

$B(\Upsilon \rightarrow X\,\gamma)$ at least for some interval of $m_X = s^{1/2}$

We use

$B(\Upsilon(3S) \rightarrow \gamma + \text{invisible}) \leq 3 \bullet 10^{-6}$ – in average is good for $s^{1/2} < 7$ GeV

Self – conjugated DM: $\Phi = \Phi^*$



line 1: $m_\Phi = 0.1$ GeV, line 2: $m_\Phi = 0.6$ GeV,
line 2: $m_\Phi = 1.5$ GeV, line 4: $m_\Phi = 3$ GeV

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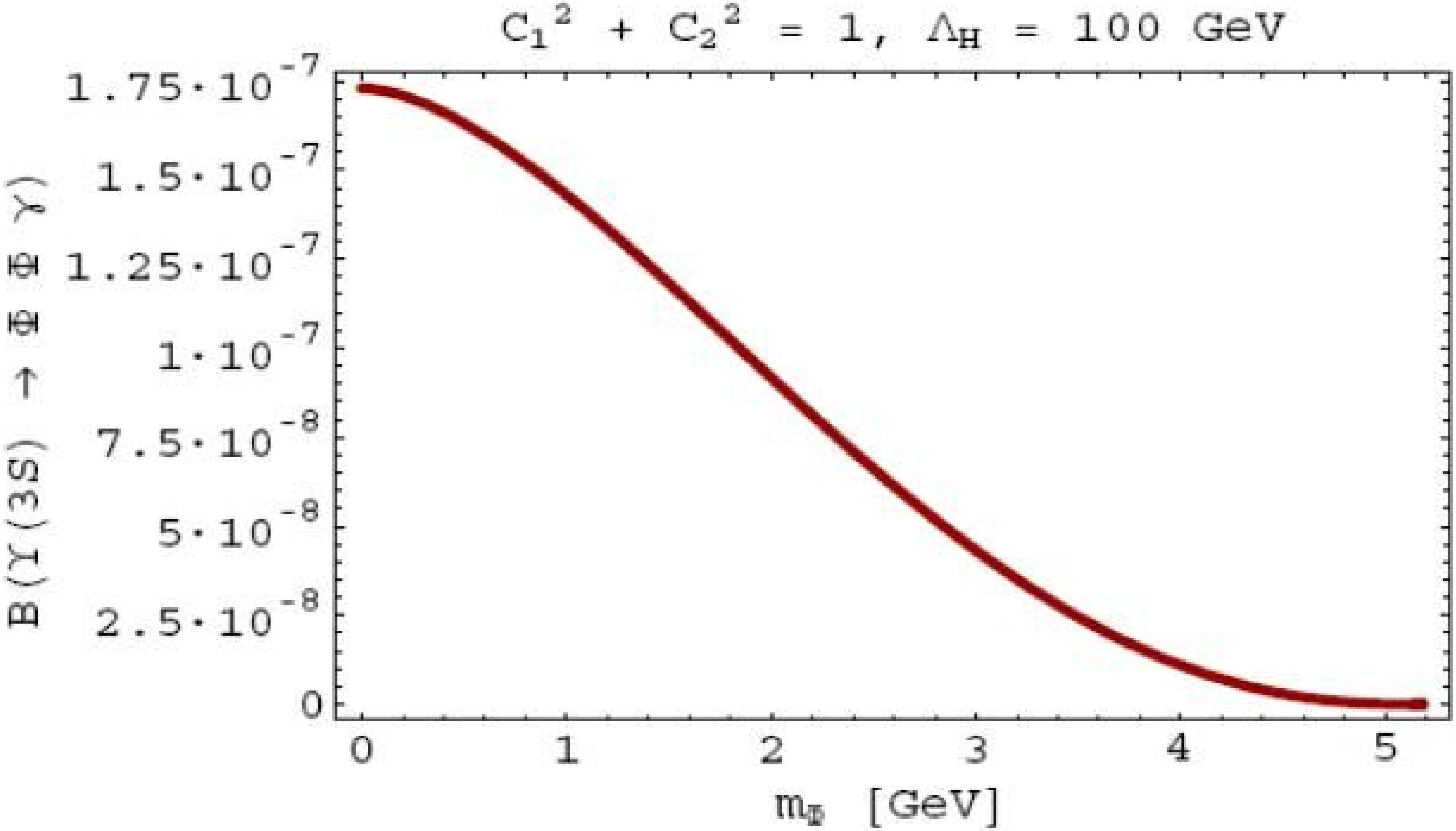

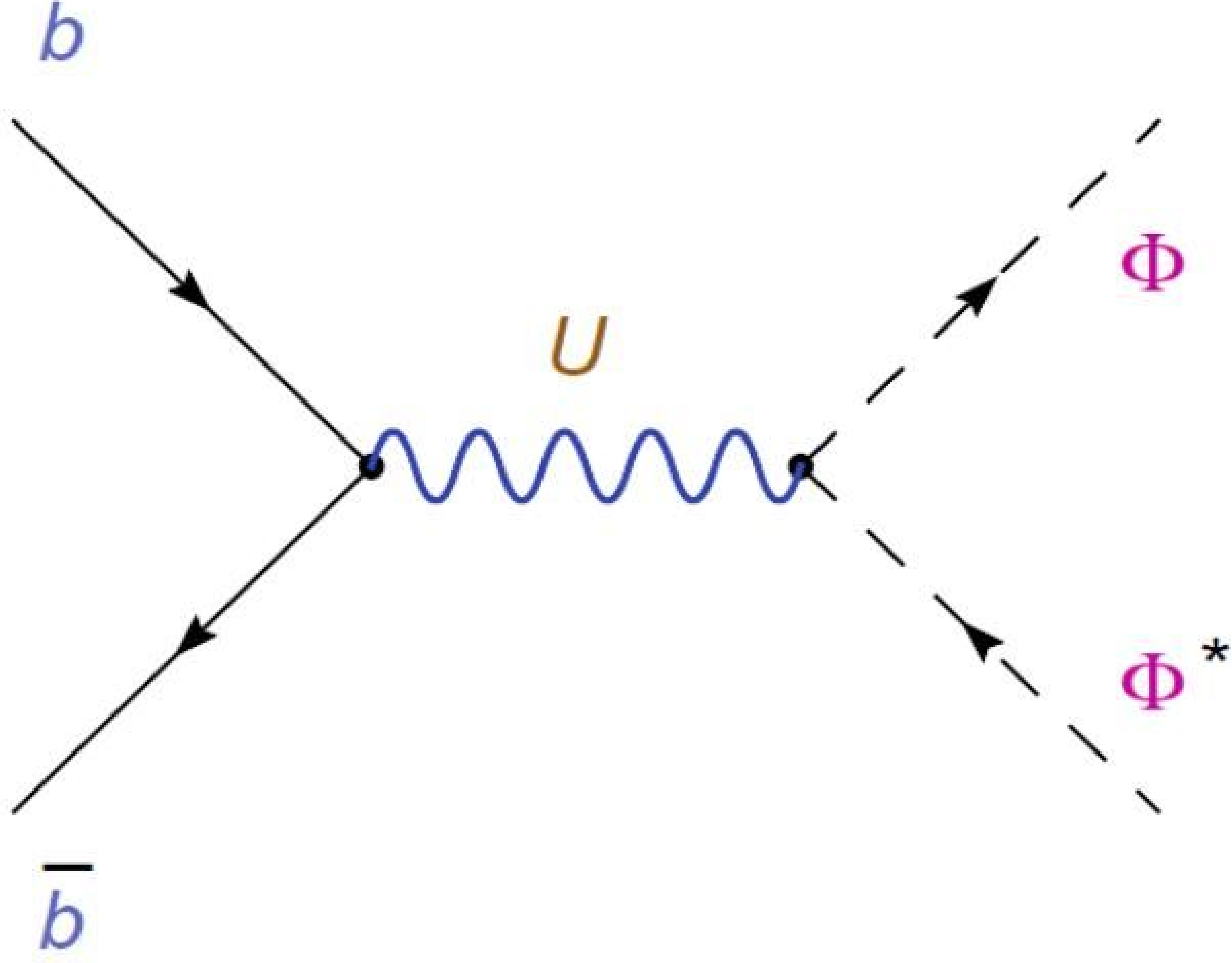

b
U
Φ
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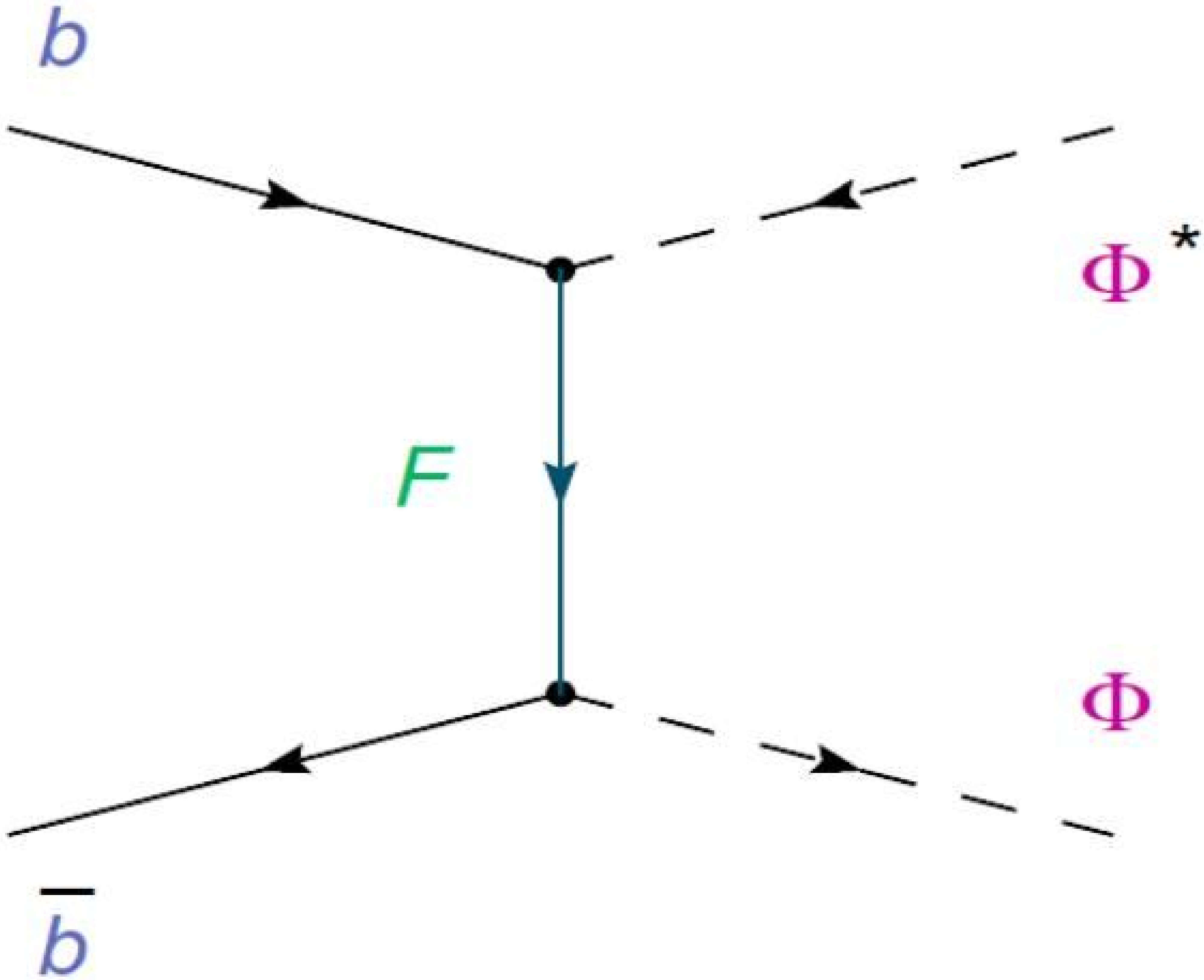
b̄


b
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