Twin Higgs model with spontaneous Z2 breaking

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based on 1510.06069 with Hugues Beauchesne and Kevin Earl

Twin Higgs

Chacko,Goh,Harnik '05

Models that try to stabilize the Higgs mass using partners that are neutral under the SM: neutral naturalness

Higgs is a pseudo-Goldstone boson of $SU(4)/SU(3)$

$$< H >= \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

Barbieri,T.G,Hall '05

Linear sigma model analysis

Mirror world:

$$\mathcal{L} = \mathcal{L}(\phi_A) + \mathcal{L}(\phi_B)$$

SM fields

$$Z_2 : \quad \phi_A \leftrightarrow \phi_B$$

The two worlds are coupled through the Higgs portal

$$|H_A|^2 \, |H_B|^2$$

Higgs potential

$$V(H_A, H_B) = \underbrace{\mu^2(|H_A|^2 + |H_B|^2) + \lambda\left(|H_A|^2 + |H_B|^2\right)^2}_{SU(4)\ \text{invariant}} + \underbrace{\alpha H_A^\dagger H_A H_B^\dagger H_B}_{SU(4)\ \text{breaking}}$$

Two possible phases:

$$\alpha > 0 \quad \longrightarrow \quad \langle H \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \mu/\sqrt{2\lambda} \end{pmatrix}$$

Z_2 broken

$$\alpha < 0 \quad \longrightarrow \quad \langle H \rangle = \begin{pmatrix} 0 \\ \mu/\sqrt{2\lambda + \alpha/2} \\ 0 \\ \mu/\sqrt{2\lambda + \alpha/2} \end{pmatrix}$$

Z_2 unbroken

again $v = f$

$$m_+^2 = 2\mu^2 = 4v^2(2\lambda + \delta) \qquad m_-^2 = 2\mu^2 \frac{\delta}{2\lambda + \delta} = 4v^2\delta$$

The Standard Model Higgs is a mixture of the A and B sectors

$$h = \frac{1}{\sqrt{2}}\left(h_A + h_B\right)$$

ruled out

Adding the Z_2 breaking term

$$\Delta m^2 \left|H_A\right|^2$$

$$\langle H \rangle = f \begin{pmatrix} 0 \\ \sin\theta \\ 0 \\ \cos\theta \end{pmatrix}$$

$$f^2 = \frac{2\mu^2 - \Delta m^2}{4\lambda + \alpha}$$

It’s possible to obtain a small ratio of vevs

$$\frac{v^2}{f^2} = \sin^2\theta = \frac{1}{2}\left(1 + \frac{\Delta m^2}{\alpha f^2}\right)$$

However it requires fine tuning

$$\Delta m^2 \sim \alpha f^2 \qquad\qquad \frac{\Delta m^2}{\alpha} = \frac{-\mu^2}{2\lambda + \alpha}$$

$$\Delta m^2_{\mathrm{max}}$$

Mass eigenstates

$$h_+ = \sin\theta H_A + \cos\theta H_B$$

$$m_+^2 = 2\mu^2 - \Delta m^2$$

$$h_- = \cos\theta H_A - \sin\theta H_B$$

$$m_-^2 = -\alpha f^2 \left(1 - \frac{\Delta m^2}{\alpha f^2}\right)^2$$

define inverse tuning as:

$$D_t = \frac{\partial \ln v^2}{\partial \ln \Lambda_t^2}$$

The cutoff can be written as:

$$\Lambda_t = D_t^{1/2} D_r^{-1/2} \frac{2\pi}{\sqrt{3}\lambda_t} m_+$$

For cutoff of Higgs quartic:

$$\Lambda_H = 1.4 \mathrm{TeV} D_H^{1/2}$$

Model with two Higgs

Introduce two 4's of SU(4)

$$H_1 = \begin{pmatrix} H_{1\,A} \\ H_{1\,B} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_{2\,A} \\ H_{2\,B} \end{pmatrix}$$

The first Higgs is given a potential that preserve Z_2

$$V_{H_1} = -\mu_1^2 H_1^\dagger H_1 + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \alpha_1 H_1{}_A^\dagger H_{1\,A} H_1{}_B^\dagger H_{1\,B}$$

$$\alpha_1 < 0$$

The second Higgs is given a potential that break Z_2

$$V_{H_2} = -\mu_2^2 H_2^\dagger H_2 + \lambda_2 \left(H_2^\dagger H_2\right)^2 + \alpha_2 H_2{}_A^\dagger H_2{}_A H_2{}_B^\dagger H_2{}_B$$

$$\alpha_2 > 0$$

The two sectors are linked by a 'Bmu' term:

$$V_{H_1 H_2} = B_\mu H_1^\dagger H_2 + \mathrm{h.c}$$

The Z2 breaking is a kind of tadpole

The vevs move from their original configuration

parametrization of the Higgs vevs

$$H_1 = f_1 \begin{pmatrix} 0 \\ \sin\theta_1 \\ 0 \\ \cos\theta_1 \end{pmatrix} \qquad H_2 = f_2 \begin{pmatrix} 0 \\ \sin\theta_2 \\ 0 \\ \cos\theta_2 \end{pmatrix}$$

$$f_1 \approx \mu_1/\sqrt{2\lambda_1} \qquad f_2 \approx \mu_2/\sqrt{2\lambda_2}$$

equations for the angles

$$\alpha_1 f_1^4 \sin 4\theta_1 + 4B_\mu f_1 f_2 \sin(\theta_1 - \theta_2) = 0$$

$$\alpha_2 f_2^4 \sin 4\theta_2 + 4B_\mu f_1 f_2 \sin(\theta_1 - \theta_2) = 0$$

If the following condition is satisfied:

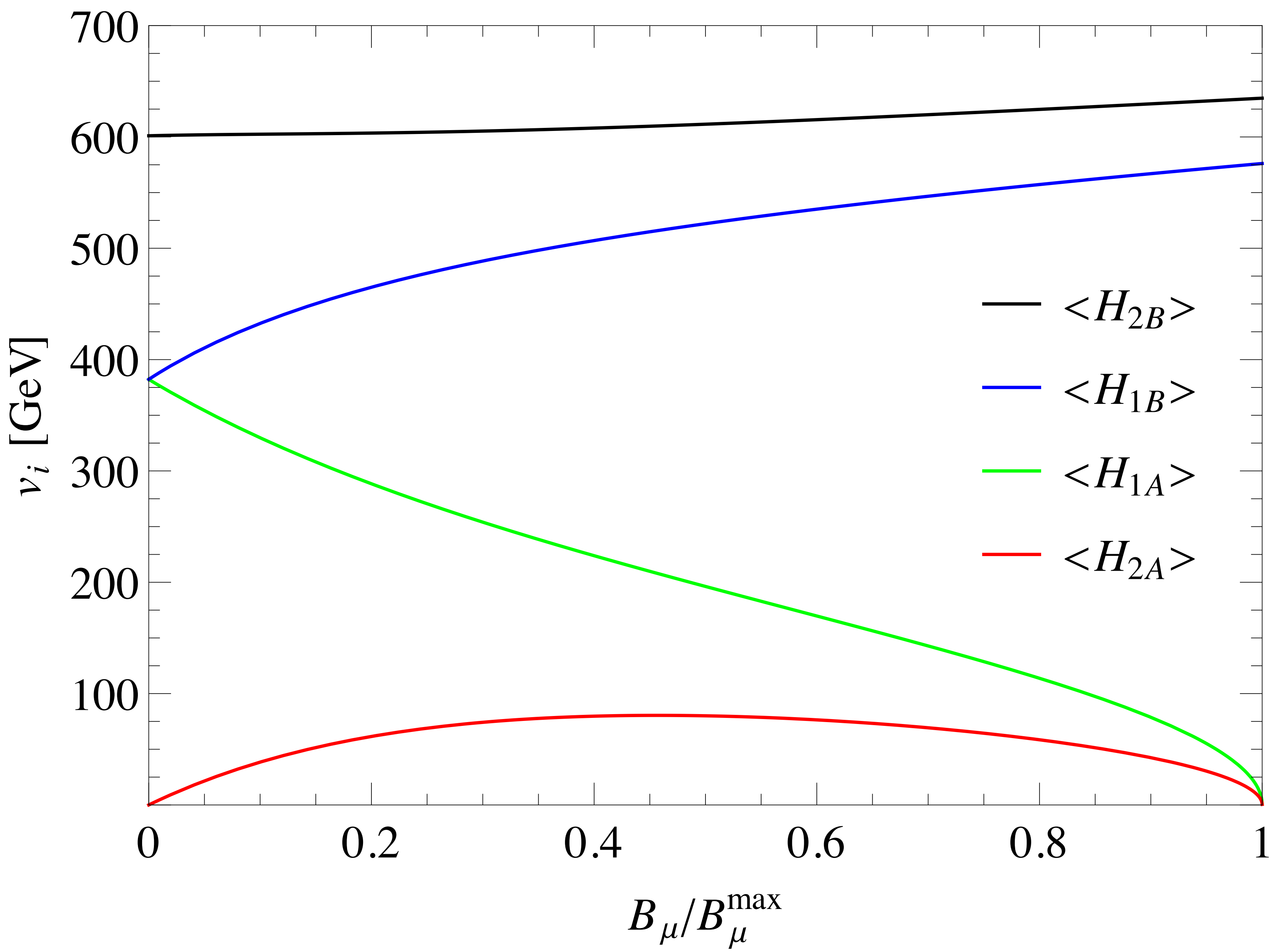
$$\frac{\alpha_1}{\lambda_1} + \frac{\alpha_2}{\lambda_2} + \frac{\alpha_1 \alpha_2}{2\lambda_1 \lambda_2} > 0$$

There is a maximal value of B_μ pass which there is no electroweak symmetry breaking

$$B_\mu^{\max} \approx -\frac{\alpha_1 f_1^3}{f_2 \left(1 - \Omega\right)}$$

with: $\Omega \equiv -\frac{\alpha_1}{\alpha_2} \left(\frac{f_1}{f_2}\right)^4$

Typical behavior of the vevs



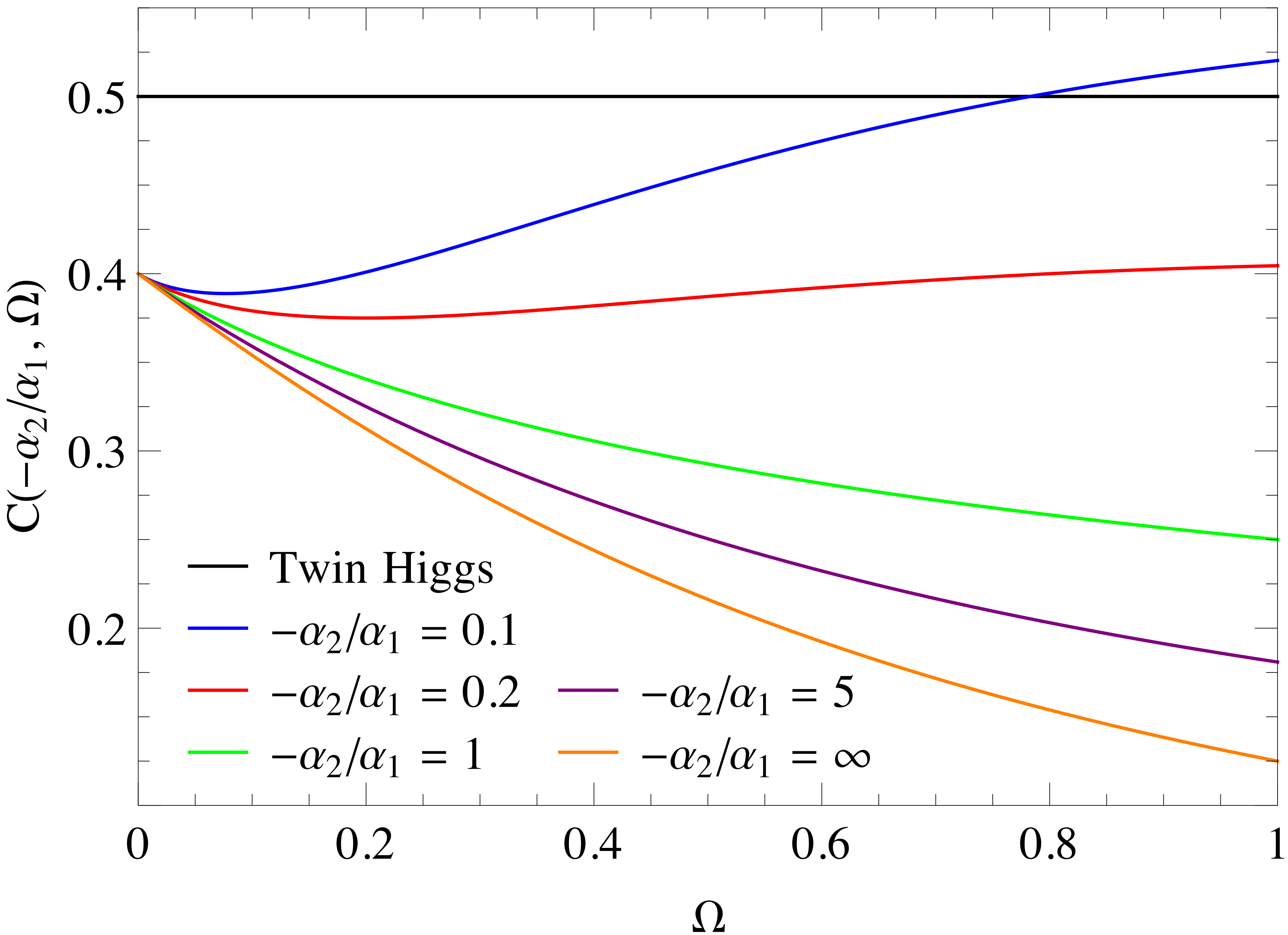
To obtain a small ratio of vevs we need to adjust B_μ close to B_μ^{max}

In the small angle limit:

$$\frac{v^2}{f_1^2} = C(-\alpha_2/\alpha_1, \Omega)\left(1 - \frac{B_\mu}{B_\mu^{\mathrm{max}}}\right)$$

some complicated function

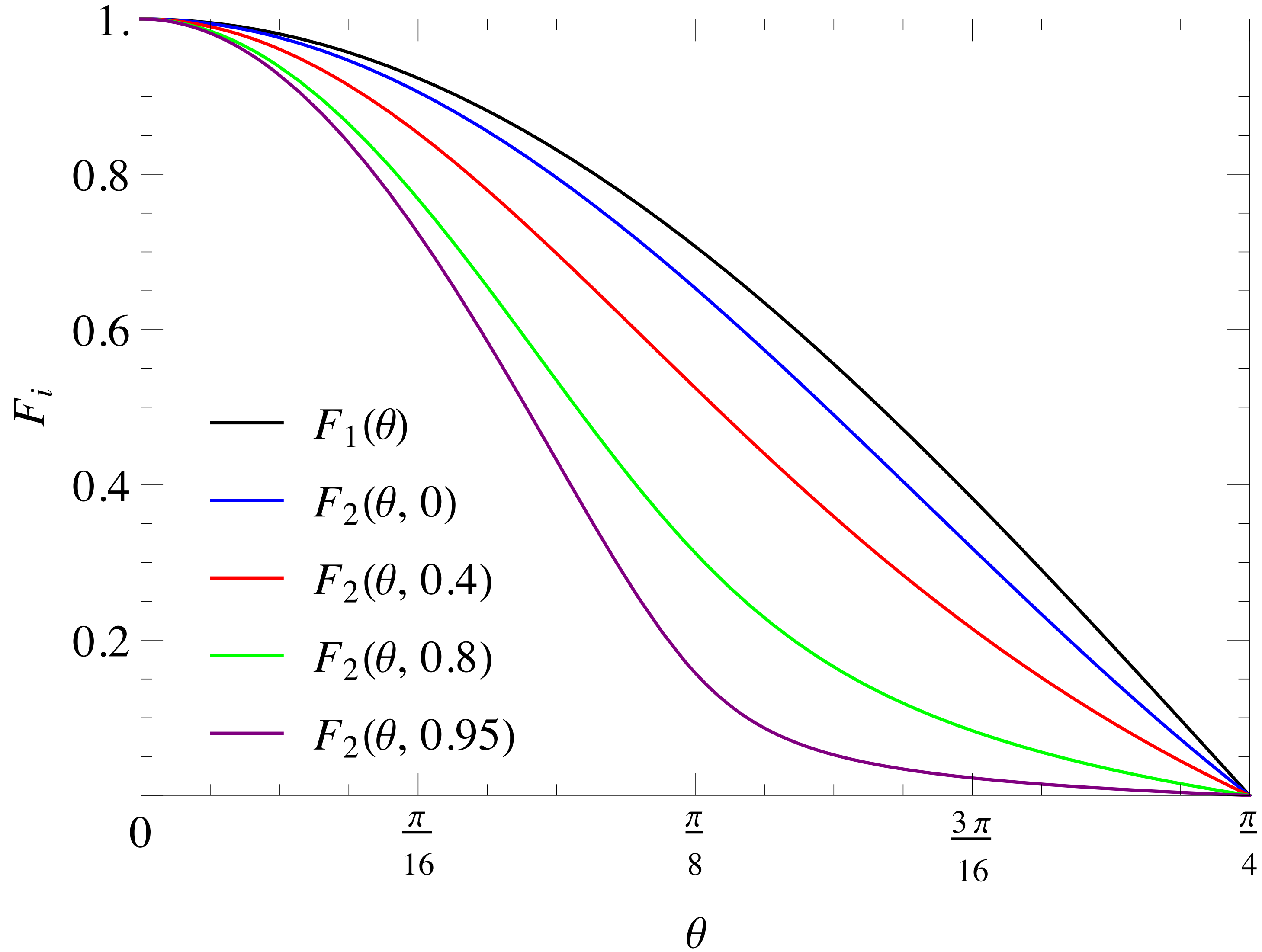
compared to: $$\frac{v^2}{f^2} = \frac{1}{2}\left(1 - \frac{\Delta m^2}{\Delta m^2_{\mathrm{max}}}\right)$$



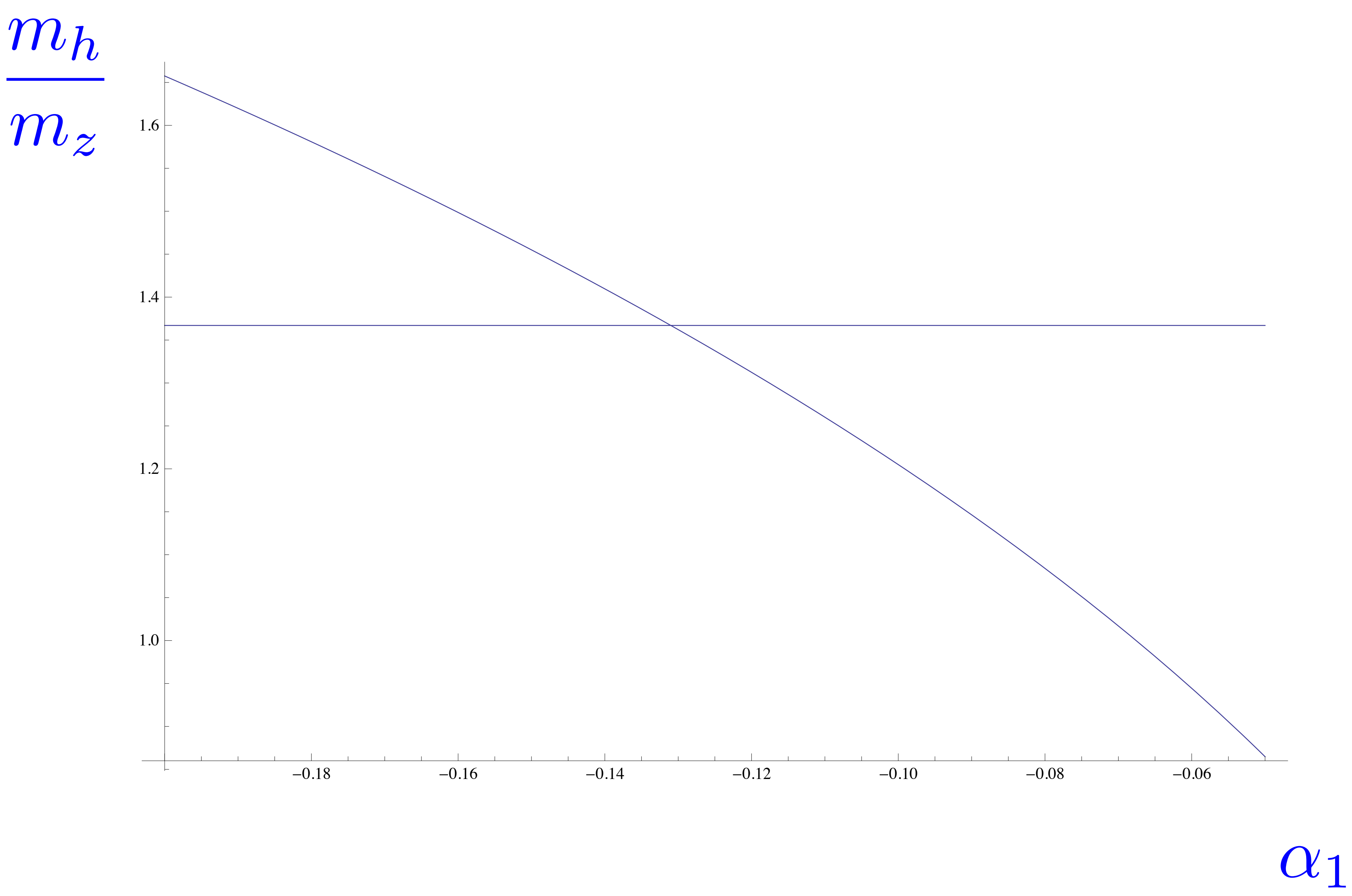
0.5
0.4
0.3
0.2
0
0.2
0.4
0.6
0.8
1
Ω
C(−α2/α1 , Ω)
Twin Higgs
−α2/α1 = 0.1
−α2/α1 = 0.2
−α2/α1 = 1
−α2/α1 = 5
−α2/α1 = ∞

going away from the small angle limit:

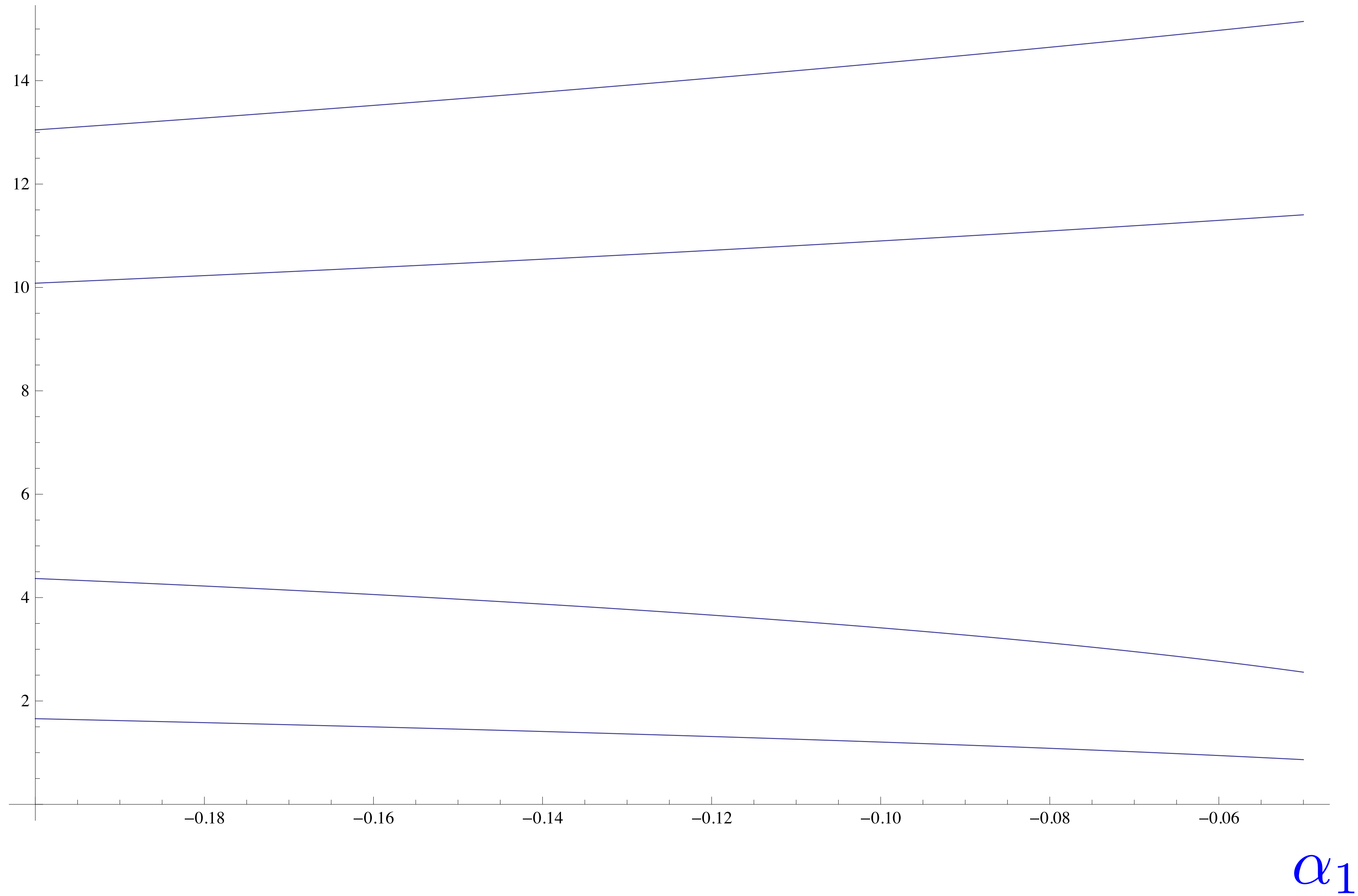
$$\frac{B_\mu}{B_\mu^{\max}} = F_2(\theta_1, \Omega)$$



Higgs mass



all Higgses

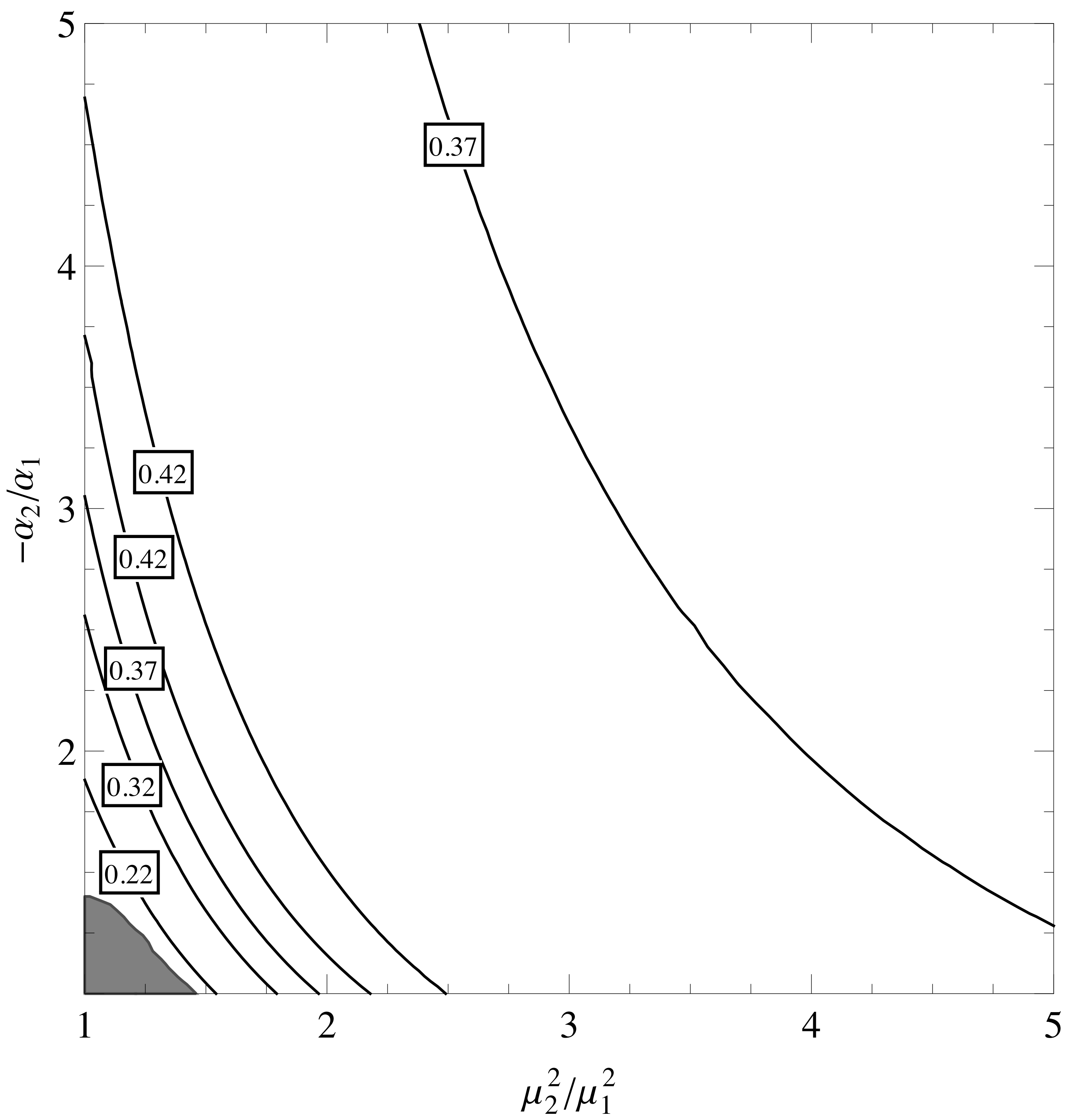


Fine-tuning study

tuning

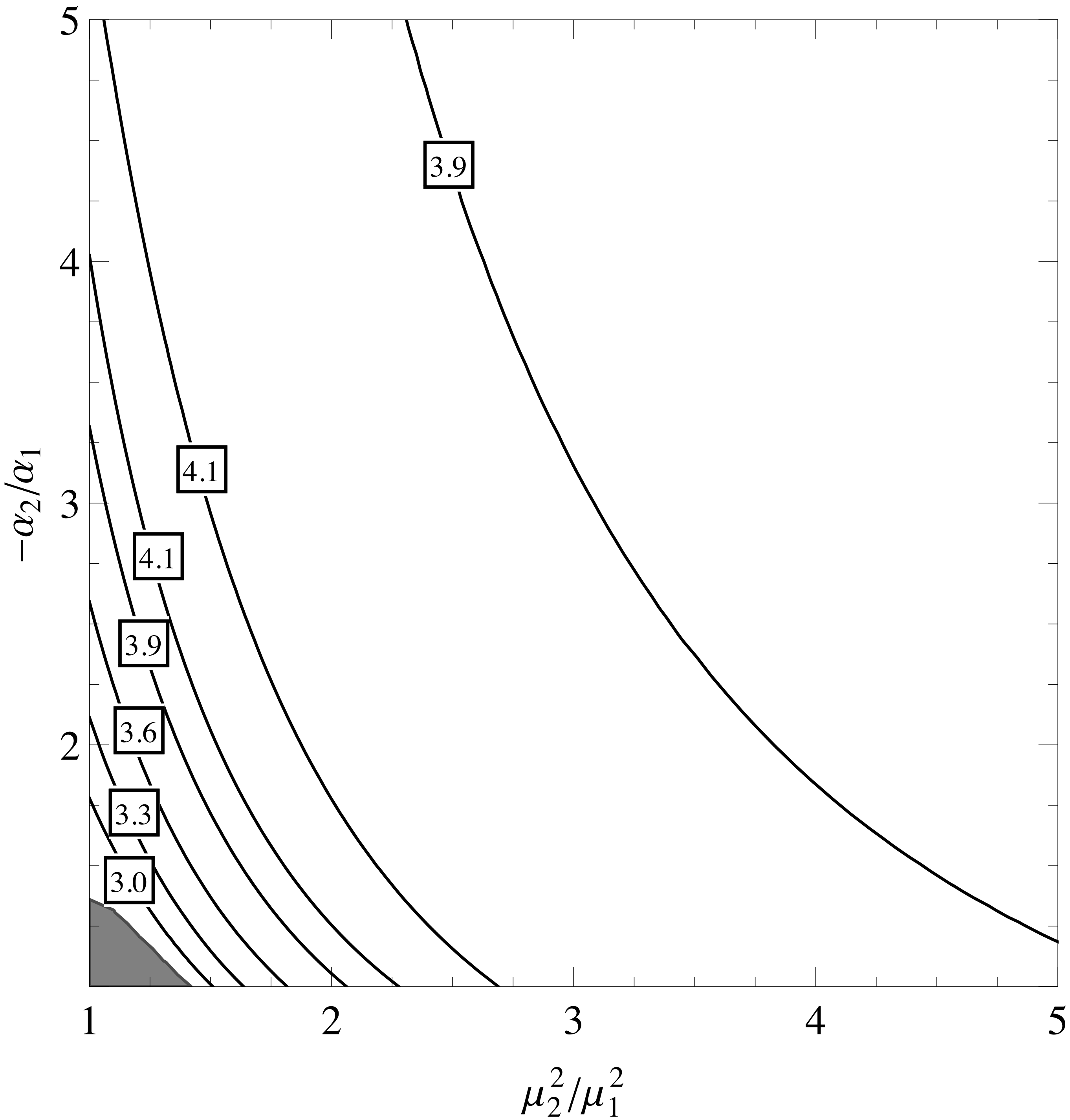
$\lambda_1 = \lambda_2 = 1$

$f_1/v = 3$



28%

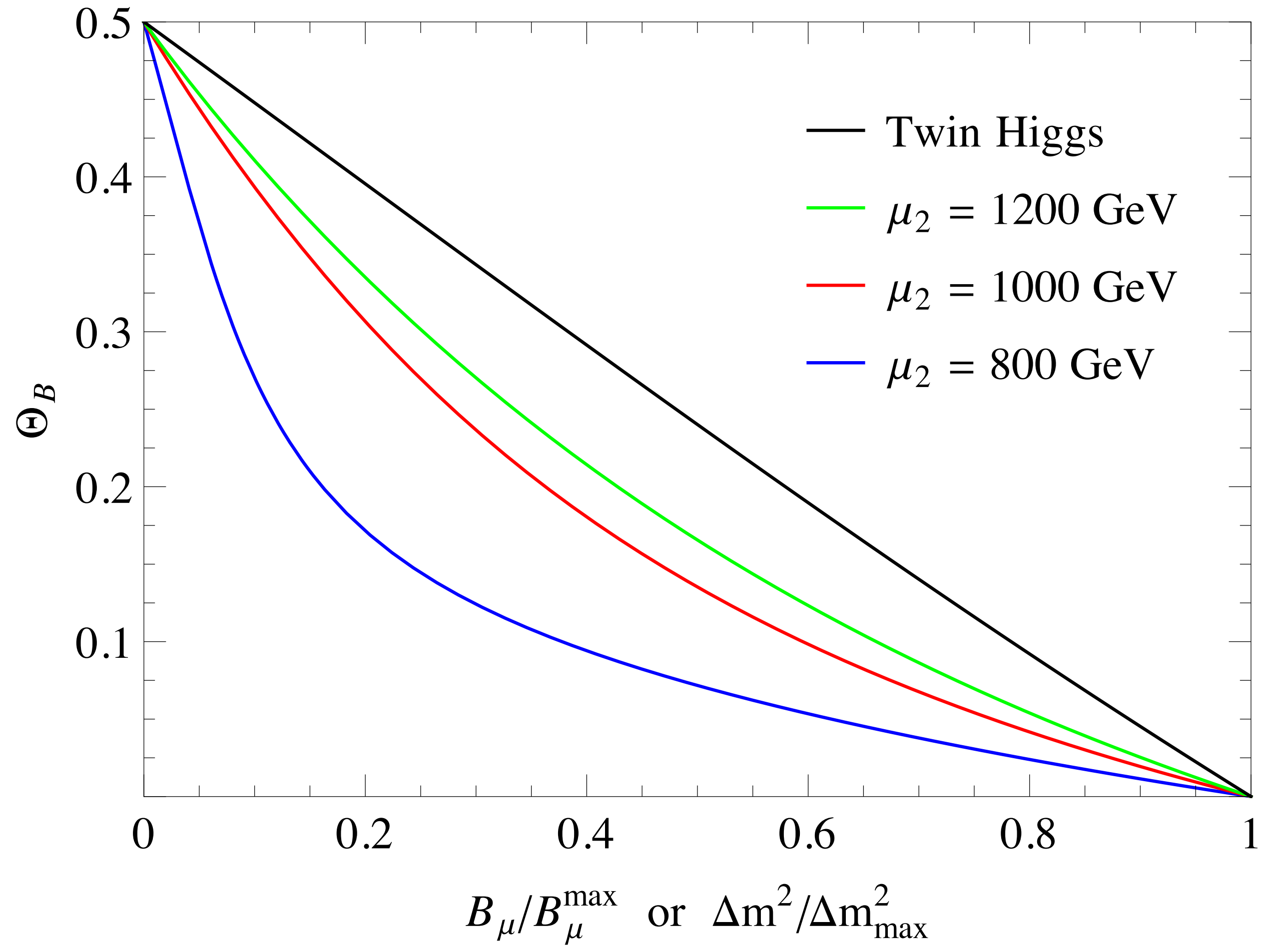
f/v for fixed tuning at 20%



The Standard Model Higgs

$$h = ah_{1A} + bh_{2A} + ch_{1B} + dh_{2B}$$

$$\Theta_B \equiv c^2 + d^2$$

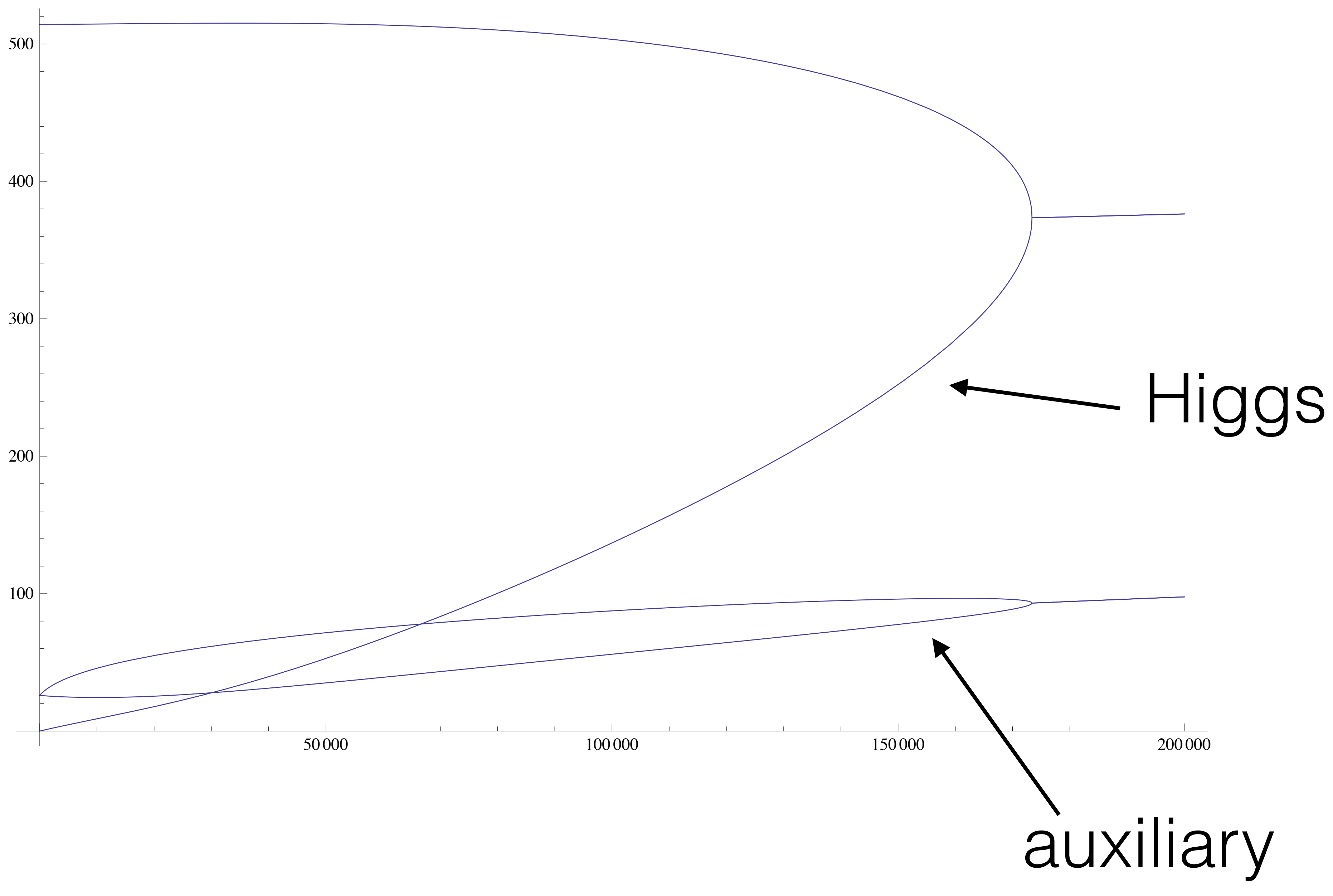


Tadpole induced EWSB: Harnik, Howe, Kearney ‘16

SM Higgs is in the Z2 breaking sector

(change the sign of α_1 and α_2)

Region of parameter space with large α_2 and small α_1


500
400
300
200
100
50 000
100 000
150 000
200 000
Higgs
auxiliary