REVISITING SCENARIOS OF IMPROVED NATURALNESS

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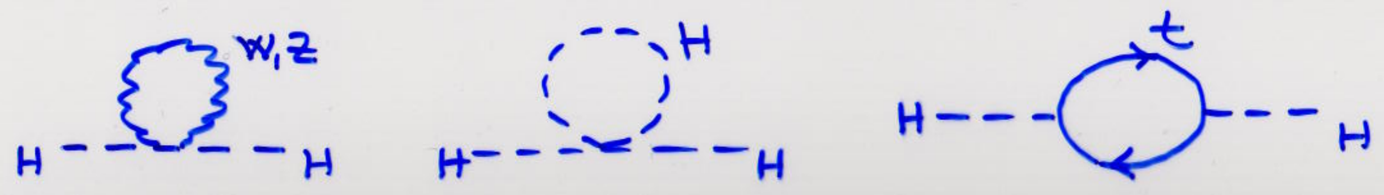
- ★ Hierarchy Problem of the Standard Model
- ★ Improved Naturalness Scenarios
  - □ Two Higgs Doublet Model
  - □ "Inert" Higgs Model
  - □ Mirror World
- ★ Conclusions

In collab. with Alberto Casas and Irene Hidalgo (IFT)
[hep-ph] to appear soon.

USING THE H.P. TO ESTIMATE THE SCALE OF NEW PHYSICS



Pestieau '78
Veltman '81
Einhorn & Jones '92

$$\delta m^2 = \frac{3\Lambda^2}{64\pi^2}\left[3g^2(\Lambda) + g'^2(\Lambda) + 8\lambda(\Lambda) - 8h_t^2(\Lambda)\right]$$

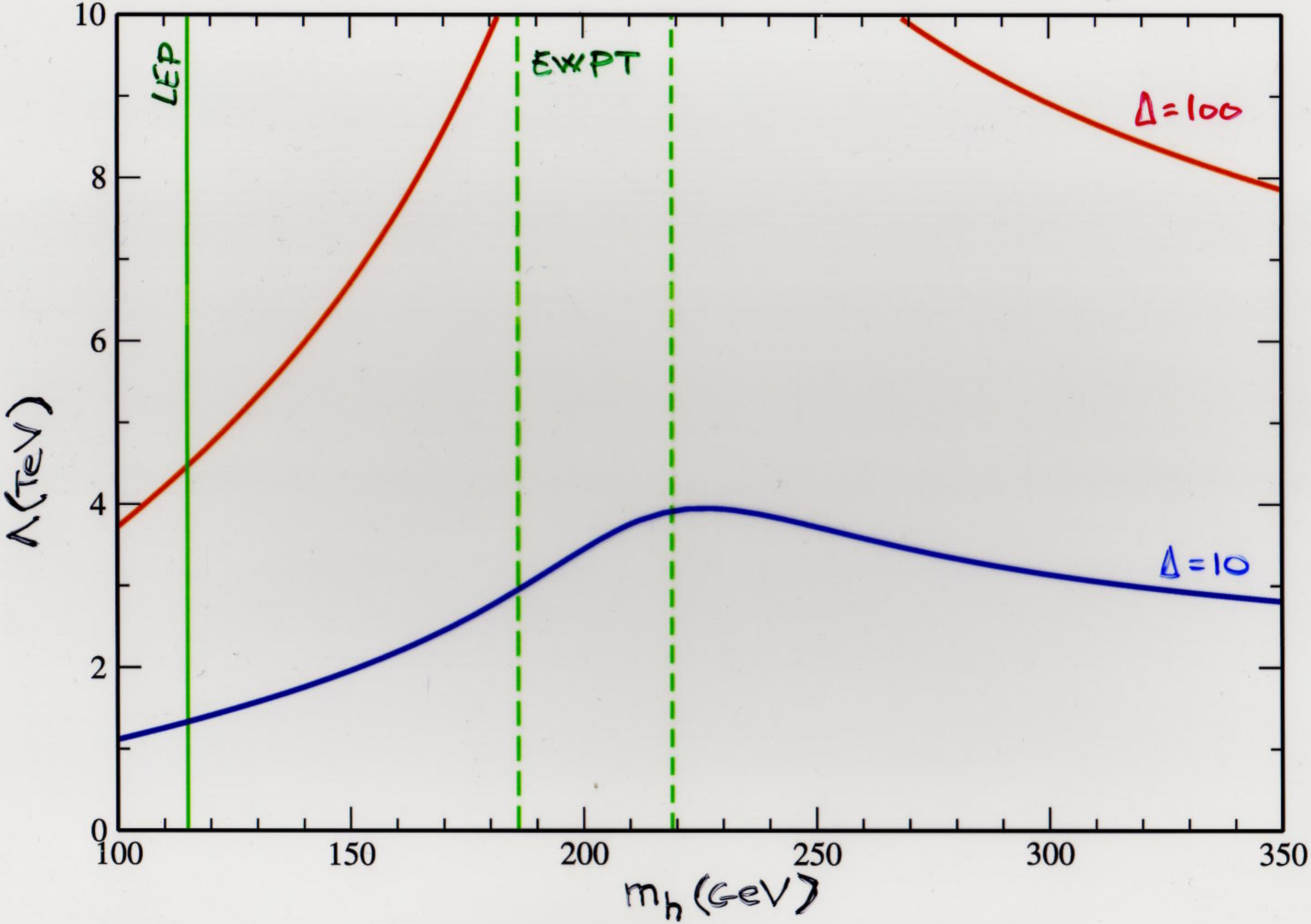
Naturalness: $\frac{\delta m^2}{m^2} < 10$ ⇨ $\Lambda \lesssim 2\text{-}3$ TeV   LHC?

Measuring Finetuning:

INPUT (UV) PARAMETERS $\{p_\alpha\}$ → YOUR FAVOURITE MODEL → $v^2 = v^2(p_1, p_2, \ldots)$ (or m^2, M_Z^2)

Use $\frac{\delta v^2}{v^2} = \Delta_{p_\alpha} \frac{\delta p_\alpha}{p_\alpha}$ → $\Delta \equiv \sqrt{\sum_\alpha \Delta p_\alpha^2}$ Accept $\Delta \lesssim 10$ (10% FT)

CUTTING VELTMAN'S "THROAT" : $\Delta \equiv \sqrt{\Delta_\Lambda^2 + \Delta_{h_t}^2 + \Delta_\lambda^2}$



CEH'04

$\Delta < 10$

⇓

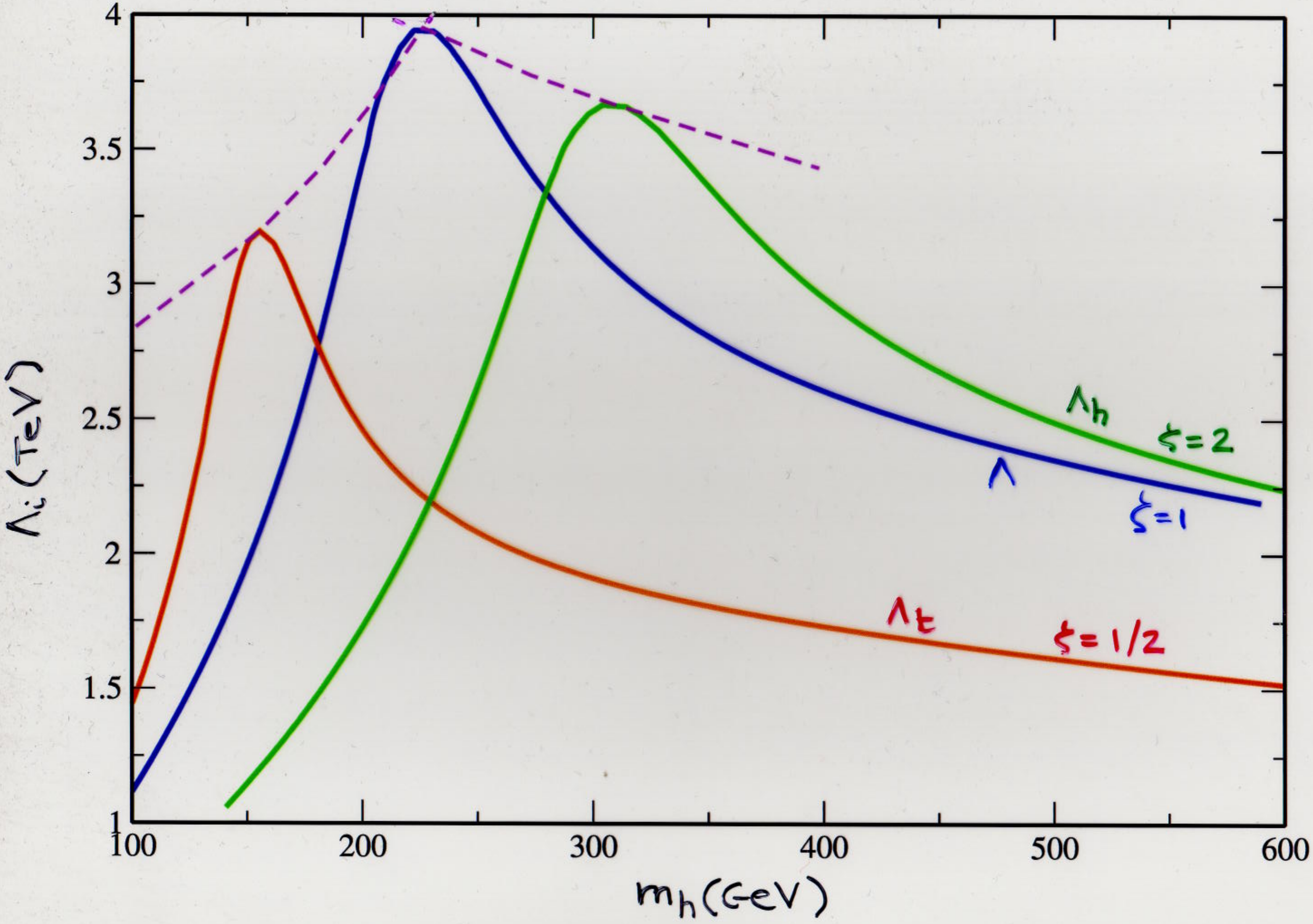
$\Lambda \lesssim 2.5-4$ TeV

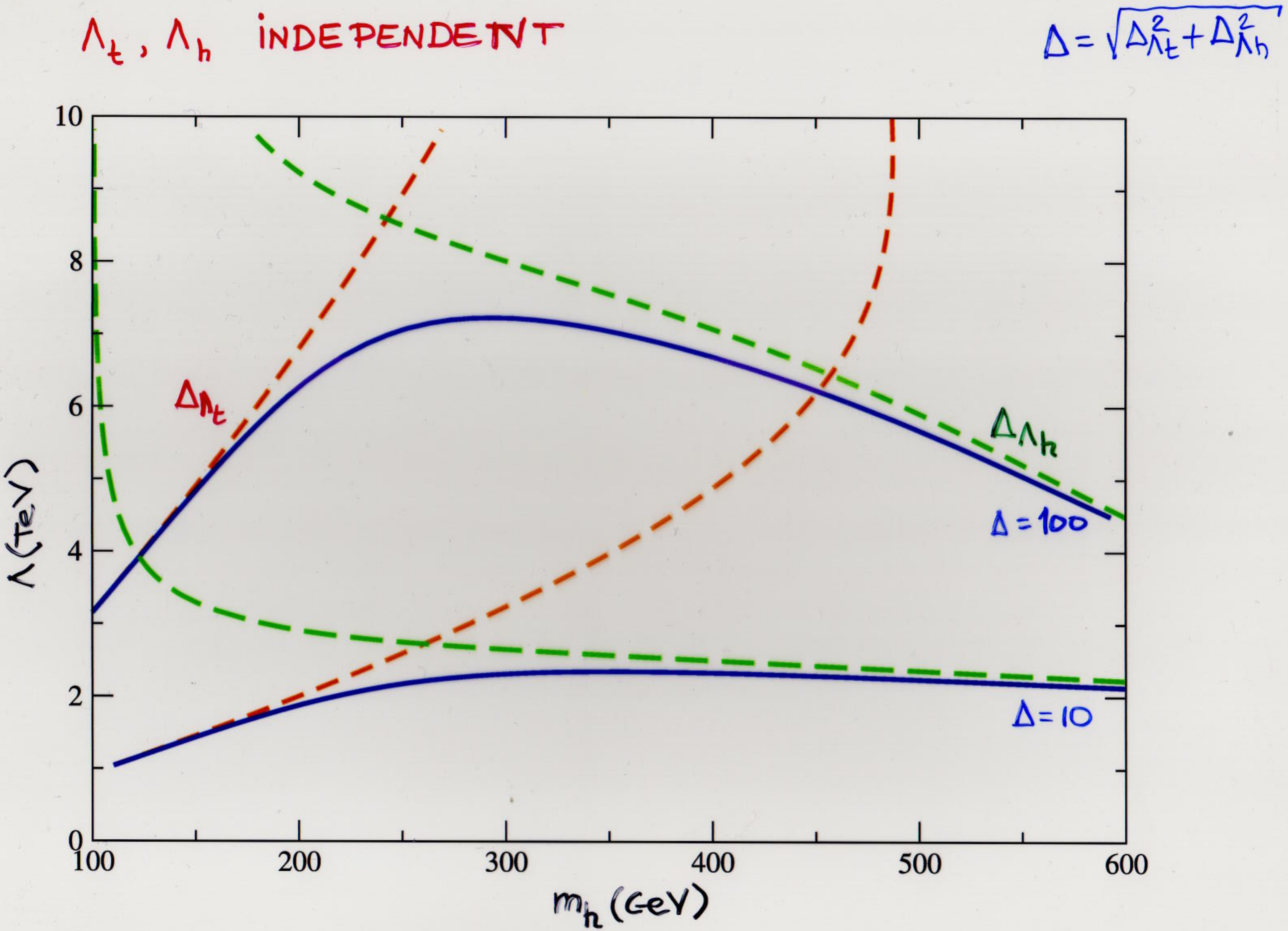
(LHC?)

PLAYING WITH THE CUTOFFS :

$\Lambda_t^2 \equiv \zeta \Lambda_h^2$

$\Delta = 10$





Λ_t , Λ_h INDEPENDENT
$\Delta = \sqrt{\Delta^2_{\Lambda_t} + \Delta^2_{\Lambda_h}}$
Λ (TeV)
m_h (GeV)
Δ_{Λ_t}
Δ_{Λ_h}
$\Delta = 100$
$\Delta = 10$
0
2
4
6
8
10
100
200
300
400
500
600

IMPROVED NATURALNESS SCENARIOS

Change Higgs Sector of Low-Energy Effective Theory to improve SM sensitivity to Λ

MODEST GOAL : raise Λ beyond the reach of LHC keeping the model natural ($\Delta \lesssim 10$)

All examples discussed here are Two-Higgs-Doublet Models

$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 +$$

$$+ \lambda_4 |H_1 \cdot H_2|^2 + \lambda_5 \left[(H_1 \cdot H_2)^2 + h.c. \right]$$

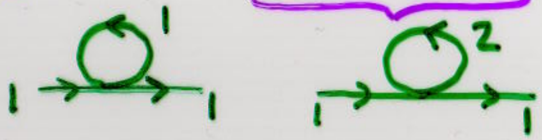
($H_2 \to -H_2$ symmetry imposed for natural flavor conservation)

I. BARBIERI & HALL MODEL [hep-ph/0510243]

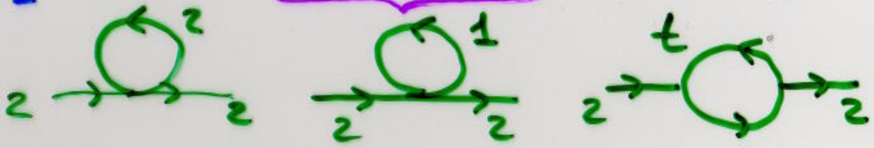
Only H_2 couples to top.

Quadratic divergences

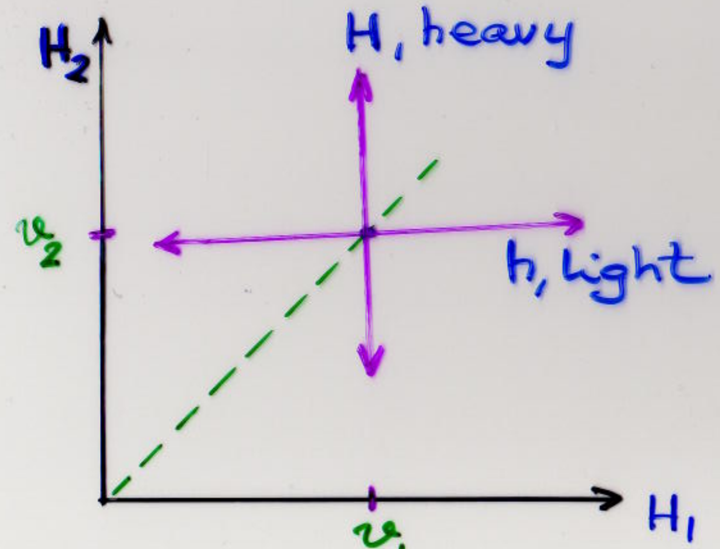
$$\delta\mu_1^2 \simeq \frac{\Lambda^2}{8\pi^2}\left[3\lambda_1 + \underbrace{\lambda_3 + \tfrac{1}{2}\lambda_4}\right]$$



$$\delta\mu_2^2 = \frac{\Lambda^2}{8\pi^2}\left[3\lambda_2 + \underbrace{\lambda_3 + \tfrac{1}{2}\lambda_4} - 3h_t^2\right]$$



SET-UP :



$v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$

- $h \sim H_1$ light, not coupled to top
  $\lambda_1\Lambda^2$ not dangerous, $h_t^2\Lambda^2$ absent
- $H \sim H_2$ heavy, coupled to top
  $\lambda_2\Lambda^2, h_t^2\Lambda^2$ less dangerous for larger μ_2^2

SOME DIFFICULTIES?

(※1) $v_1, v_2 < v$ harder to be natural

(※2) $m_A^2 = -2\lambda_5 v^2$ $\quad m_{H^+}^2 = -\frac{1}{2}(\lambda_4 + 2\lambda_5)v^2 \gtrsim (200\,\mathrm{GeV})^2$ $(b \to s\gamma)$

$$M_{h,H}^2 = \begin{bmatrix} 2\lambda_1 v_1^2 & \delta v_1 v_2 \\ \delta v_1 v_2 & 2\lambda_2 v_2^2 \end{bmatrix} \to \lambda_3 + \lambda_4 + 2\lambda_5 \text{ wanted small}$$

requires a cancellation with λ_3 which won't be small ⇨ $\lambda_3 \Lambda^2 \ldots$

(※3) $m_H^2 \simeq 2\lambda_2 v_2^2$ heavy, requires sizable λ_2 which gets even larger at Λ (remember $\lambda_2(\Lambda)\cdot\Lambda^2$)

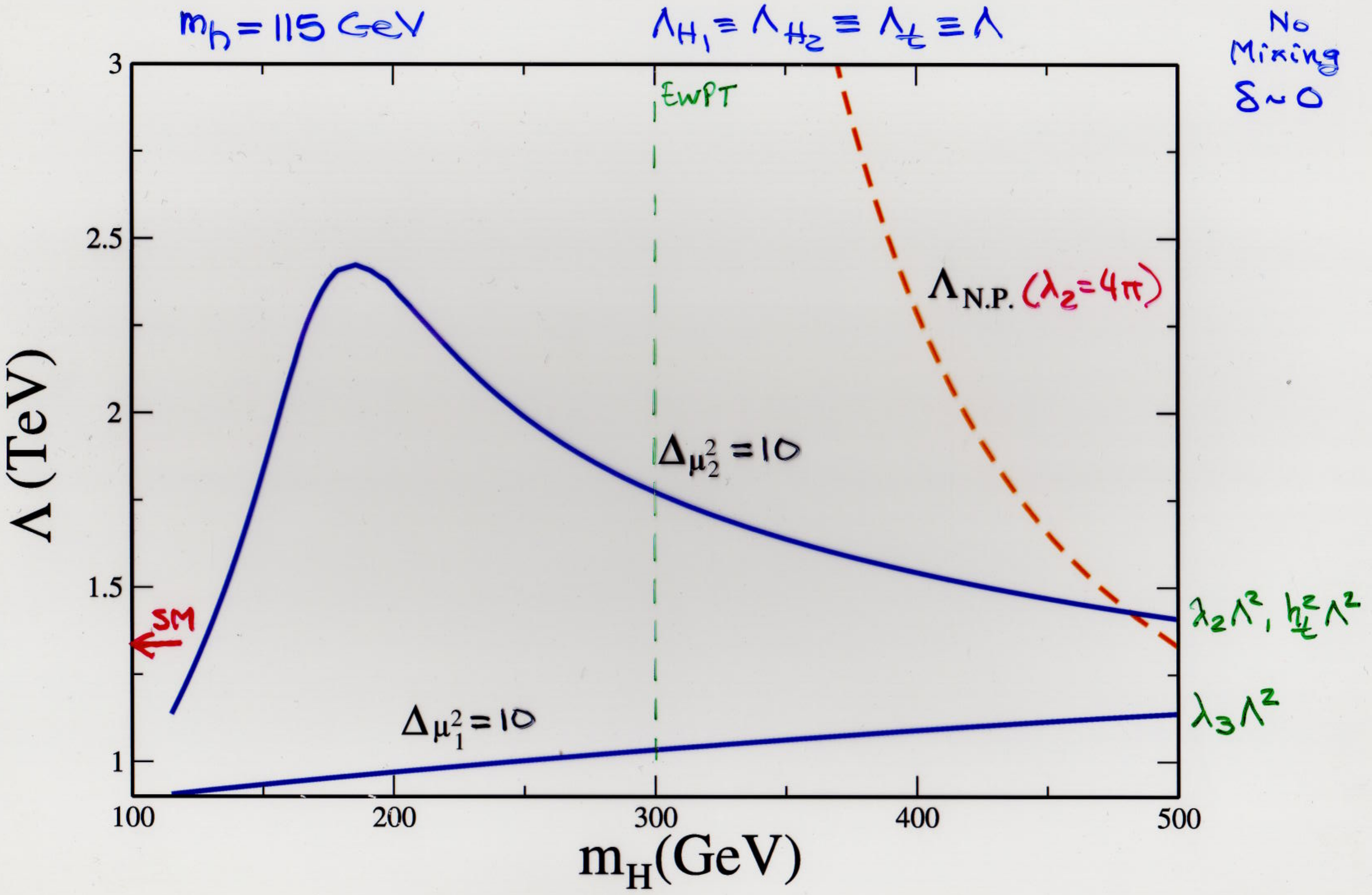
(※4) λ_2 hits a Landau pole not far from Λ

⇨ hints at strongly coupled interactions not far from EW scale

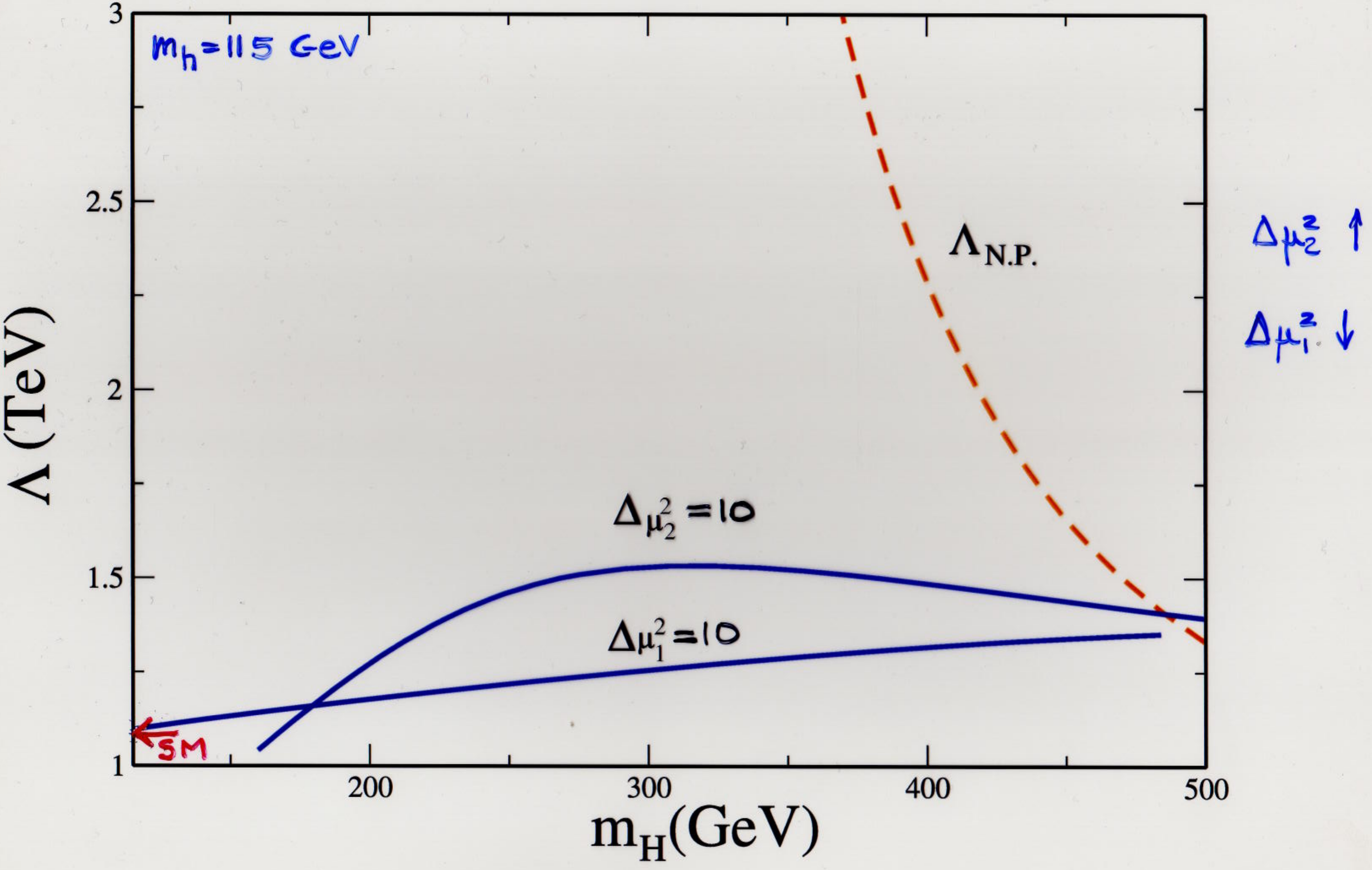
(※5) EWPT : $\log m_h \to c_\beta^2 \log m_h + s_\beta^2 \log m_H$ ⇨ $m_H < m_h \left(\frac{186\,\mathrm{GeV}}{m_h}\right)^{\frac{1}{s_\beta^2}}$

"IMPROVED NATURALNESS" MODEL

Barbieri-Hall '05



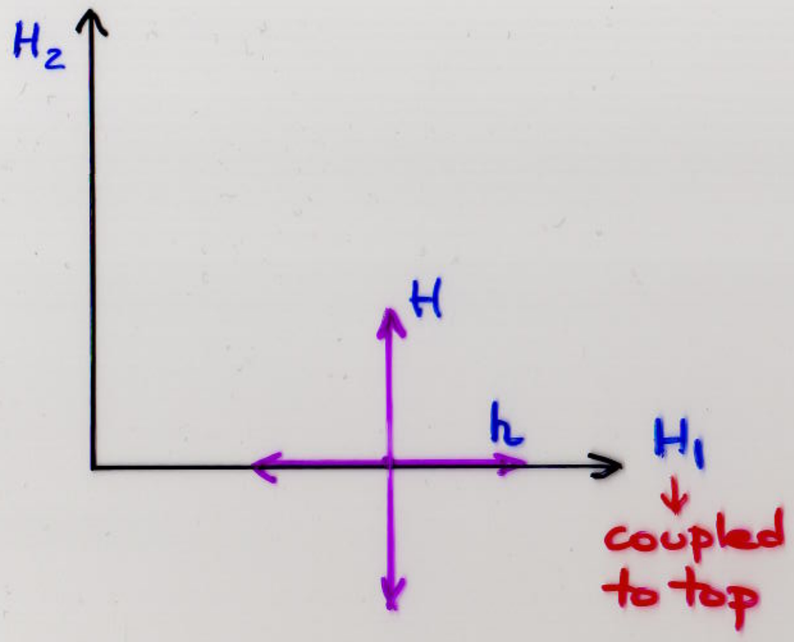
INDENDENT CUTOFFS: $\Lambda_{H_1}, \Lambda_{H_2}, \Lambda_t$



II. "INERT HIGGS" MODEL

Barbieri, Hall & Rychkov [hep-ph/0603188]

SET-UP :



- $h = H_1$ heavy (400–600 GeV) & coupled to top

  $\lambda_1 \Lambda^2,\ h_t^2 \Lambda^2$ less dangerous for larger μ_1^2 (but gives problems with EWPTs)

- $H = H_2$ not involved in EWSB but helps in EWPT (better heavy for naturalness)

$$\Delta T \simeq 0.25$$

$$\Downarrow$$

$$(m_{H^+} - m_{A^0})(m_{H^+} - m_{H^0}) \sim (120\ \text{GeV})^2$$

(reasonable : $\Delta m^2 \sim \lambda_i v^2$)

$m_L \equiv \min(m_{A^0}, m_{H^0}) < m_{H^+}$

Possible DM candidate

DIFFICULTIES ?

#1 $v = 246\ \text{GeV}$ Like in SM ✓ OK

#2 λ_1 starts large and grows in the UV more quickly than in the SM: $\lambda_1(\Lambda)\Lambda^2$ dangerous for μ_1^2

#3 Small $\lambda_3, \lambda_4, \lambda_5$ preferred, to slow down λ_1 growth and to keep $(\lambda_3 + \frac{1}{2}\lambda_4)\Lambda^2$ under control

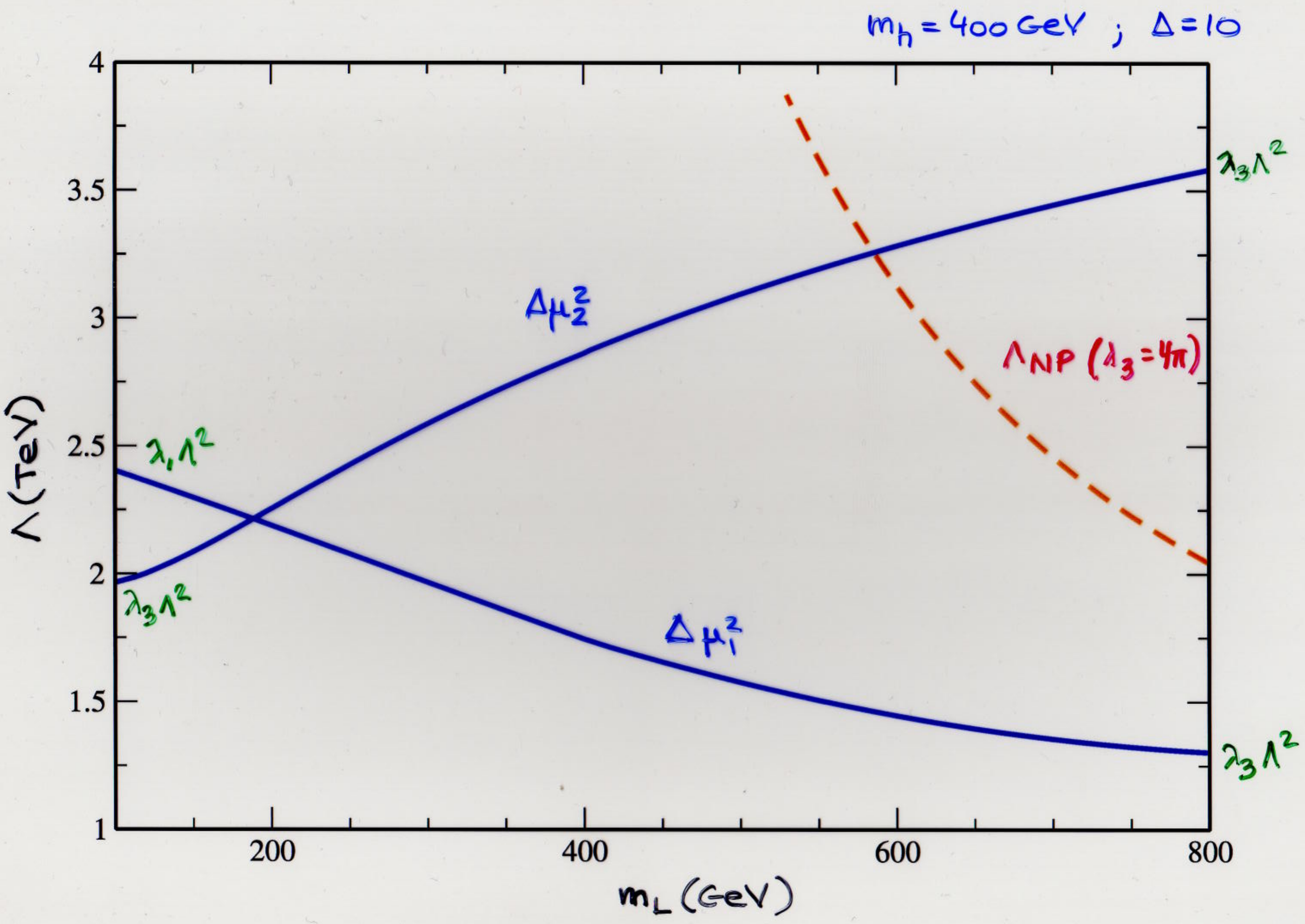
BUT they cannot be too small if $\Delta T \sim +0.25$

⇩

$\lambda_3 \Lambda^2$ dangerous

ESpecially for μ_1^2 if m_L not small

"INERT" HIGGS MODEL



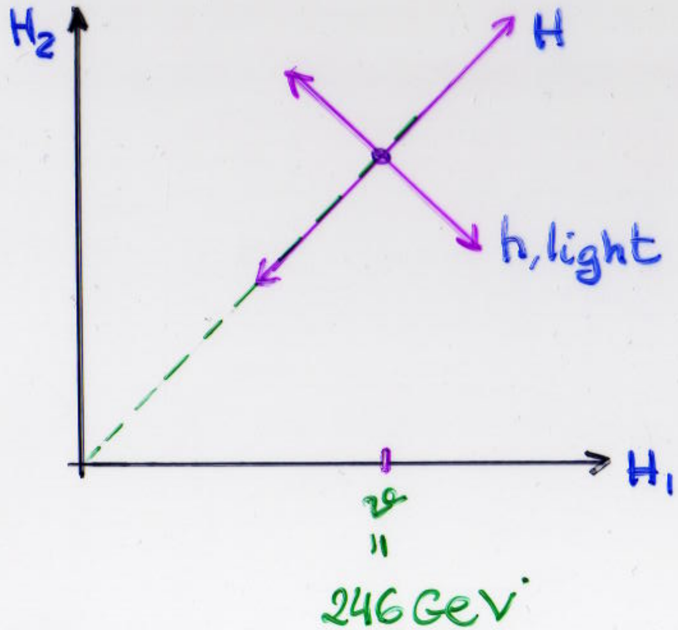
MIRROR WORLD MODEL

Barbieri, Gregoire & Hall [hep-ph/0509242]

$$SM \xrightarrow{Z_2} SM'$$

$$H_1 \longrightarrow H_2 \equiv H_1'$$

$$V = \mu^2(|H_1|^2+|H_2|^2) + \lambda(|H_1|^2+|H_2|^2)^2 + \delta[|H_1|^4+|H_2|^4]$$



- $\{H, h\} = \frac{1}{\sqrt{2}}(H_1 \pm H_2)$ have reduced couplings in our world

$$m_H^2 = (2\lambda+\delta)\,2v^2 \,, \quad m_h^2 = 2\delta v^2$$

Take $\delta \ll \lambda$

$$\delta\mu^2 \simeq \frac{\Lambda^2}{8\pi^2}\left[5\lambda + 3\delta - 3h_t^2\right] \,, \quad 2\mu^2 = m_H^2$$

DIFFICULTIES ?

※1 VEV is $2v^2$ ... No advantage w.r.t. SM

※2

$$\delta\mu_H^2 \simeq \frac{3\Lambda^2}{4\pi^2 v^2}\left[\frac{5m_H^2+m_h^2}{24} - m_t^2\right] \quad \text{vs.} \quad \delta\mu_h^2 \simeq \frac{3\Lambda^2}{4\pi^2 v^2}\left[\frac{m_h^2}{4} - m_t^2\right]$$

Quite similar to SM (a bit better for $m_H^2 \gg m_h^2$)

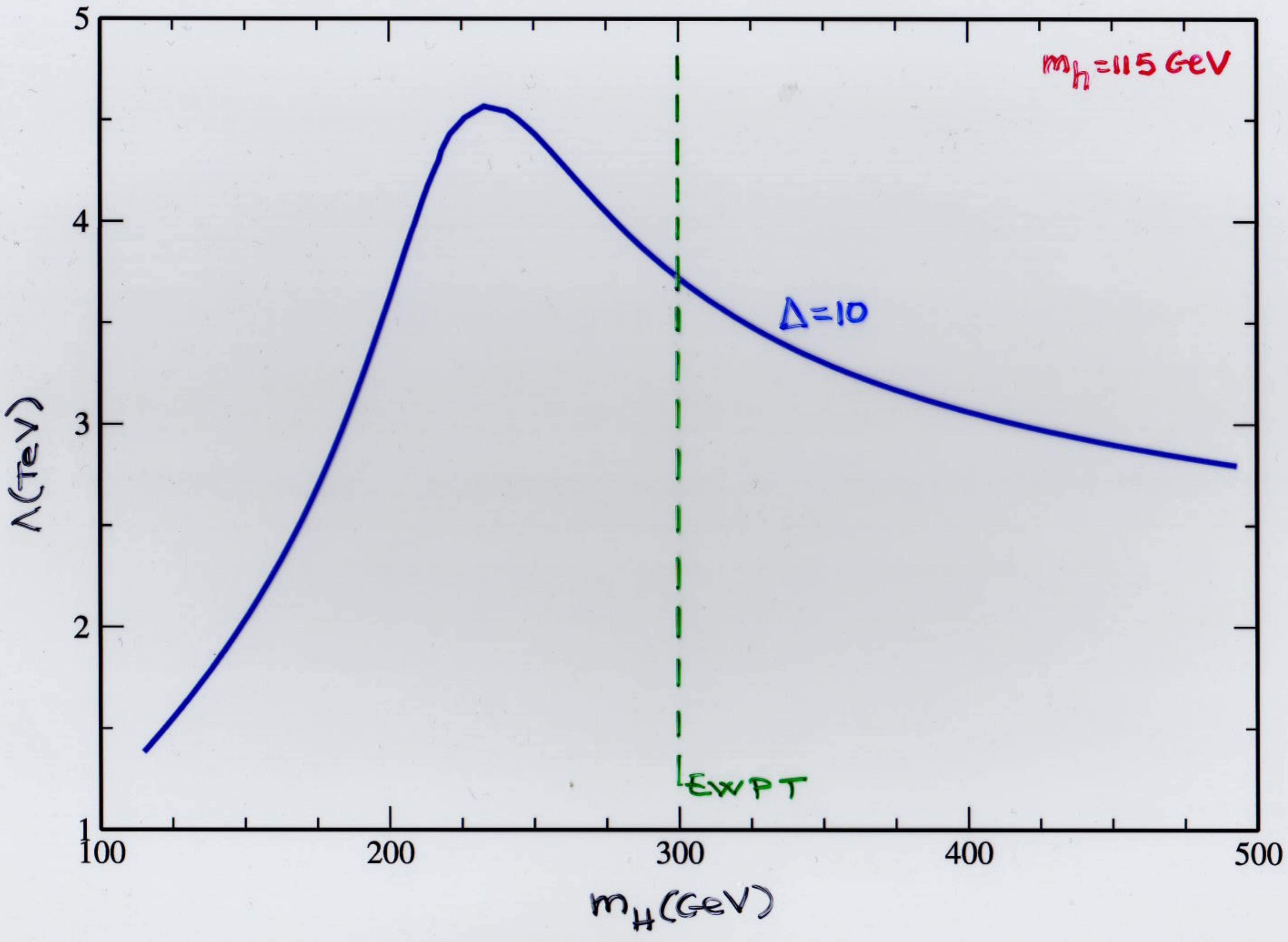
※3 RGE effects less strong than in SM

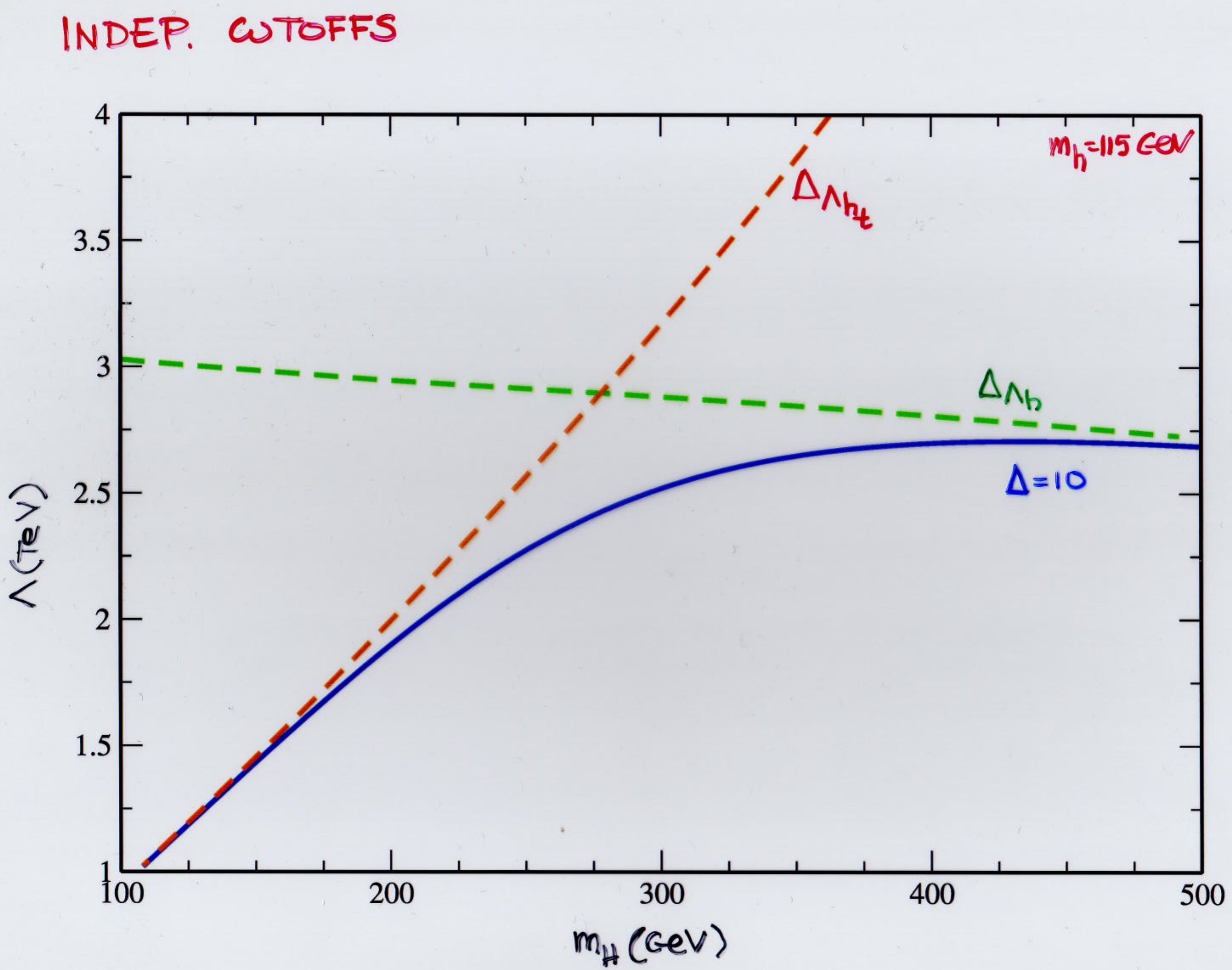
※4 EWPT Bound on m_H is less severe :

$$\log m_h \rightarrow \frac{1}{2}\log m_h + \frac{1}{2}\log m_H$$

⇨ $m_H m_h \lesssim (186\ \text{GeV})^2$ ⇨ $m_H \lesssim 300$ GeV for $m_h = 115$ GeV

MIRROR WORLD





INDEP. CUTOFFS
m_h=115 GeV
Δ_{Λh_t}
Δ_{Λh}
Δ=10
4
3.5
3
2.5
2
1.5
1
100
200
300
400
500
Λ (TeV)
m_H (GeV)

CONCLUSIONS

If we believe EWSB is natural, an upper bound on the scale of New Physics, follows, $\Lambda \sim$ few TeV

- ★ Already in the SM $\Lambda \lesssim 3$ TeV for m_h close to its upper limit from EWPT
  (or $\Lambda \lesssim 4$ TeV if physics at Λ balances ΔT)

- ★ Scenarios for "improved naturalness" do not change this situation dramatically (RG effects very important) and have tunings similar (or worst) than the SM.
  - "Mirror World" can raise $\Lambda \sim 4.5$ TeV but it's a bit speculative...

- ★ CAVEATS these low-energy eff. theory estimates are conservative (miss log effects beyond Λ).
  + they are sensitive to assumptions about Λ_t, Λ_h...