

STABILITY OF THE EW VACUUM



BSM and Higgs Physics at the LHC
ICTP Workshop
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STABILITY OF THE EW VACUUM AFTER LHC

- ★ Status after first LHC run
Higgs discovered, no trace of BSM...
- ★ $M_h \approx 126$ GeV \Rightarrow EW Vacuum unstable
- ★ Several implications of this instability
- ★ A simple fix (robust and well motivated)

Based on :

J. Elias-Miró , J.R.E , G.F. Giudice , G. Isidori , A. Riotto , A. Strumia
[hep-ph/1112.3022],
J. Elias-Miró , J.R.E , G.F. Giudice , H.M. Lee , A. Strumia
[hep-ph/1203.0237]
G. Degrassi , S. Di Vita , J. Elias-Miró , J.R.E , G.F. Giudice ,
G. Isidori , A. Strumia , [hep-ph/1205.6497]

For recent related work see :

M. Holthausen , K.S. Lim , M. Lindner [hep-ph/1112.2415]
F. Bezrukov , M.Y. Kalmykov , B.A. Kniehl , M. Shaposhnikov [hep-ph/1205.2893]
S. Alekhin , A. Djouadi , S. Moch [hep-ph/1207.0980]
O. Lebedev , [hep-ph/1203.0156]

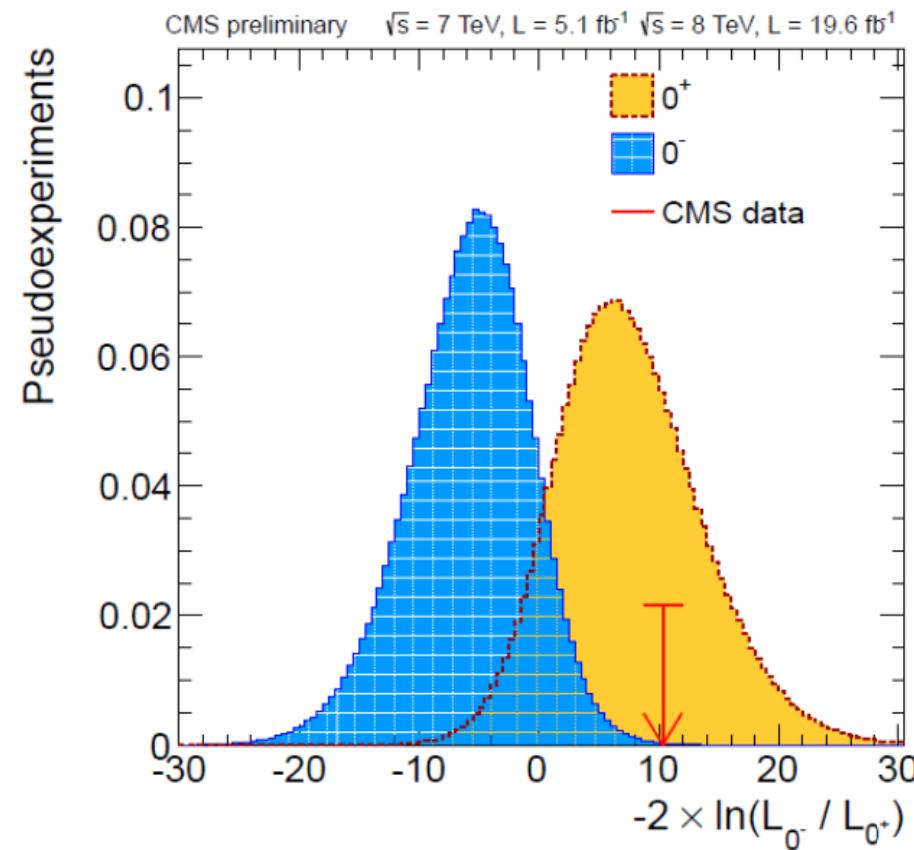
HIGGS BOSON

h^0

HIGGS BOSON

h^0

$J^P = 0^+$



0^- disfavored

HIGGS BOSON

h^0

$J^P = 0^+$

h^0 MASS

VALUE (GeV)

DOCUMENT ID

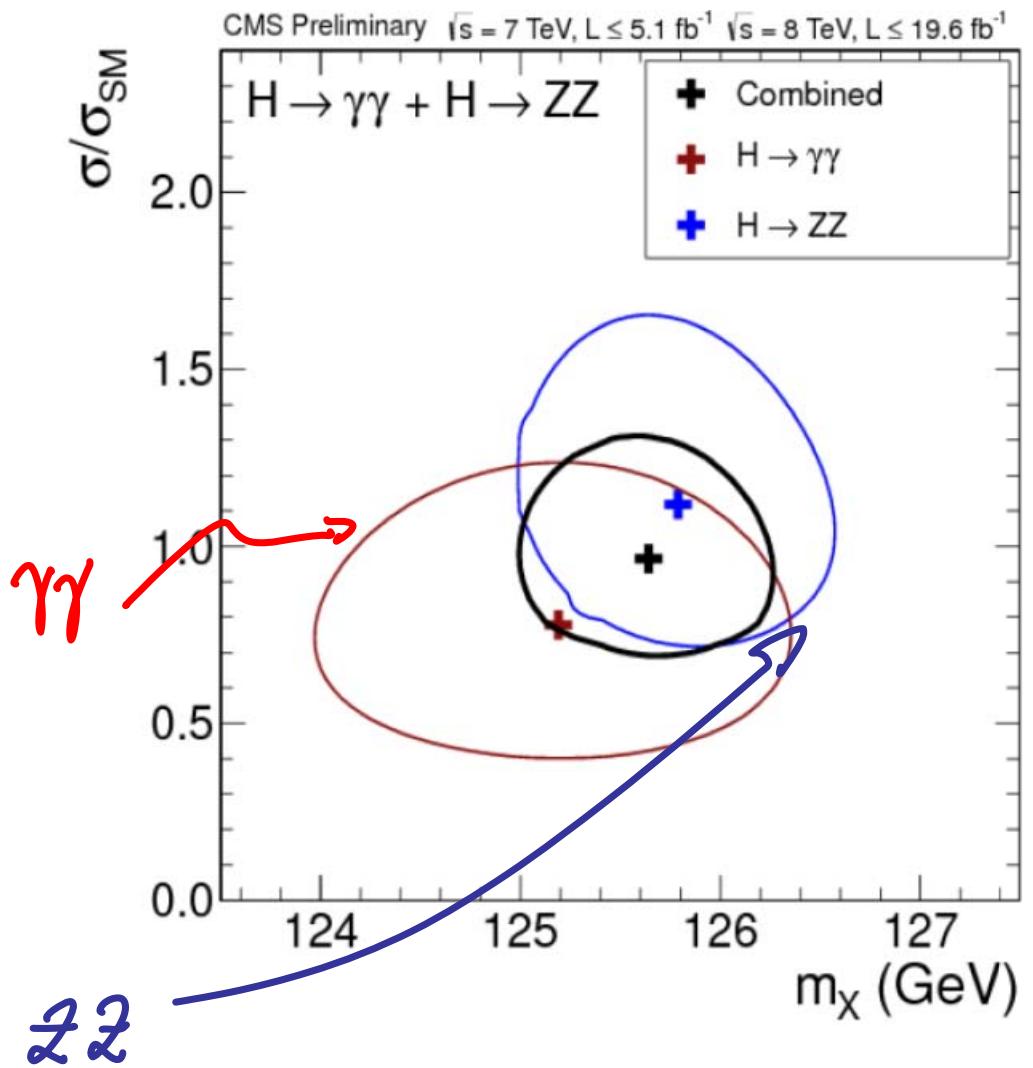
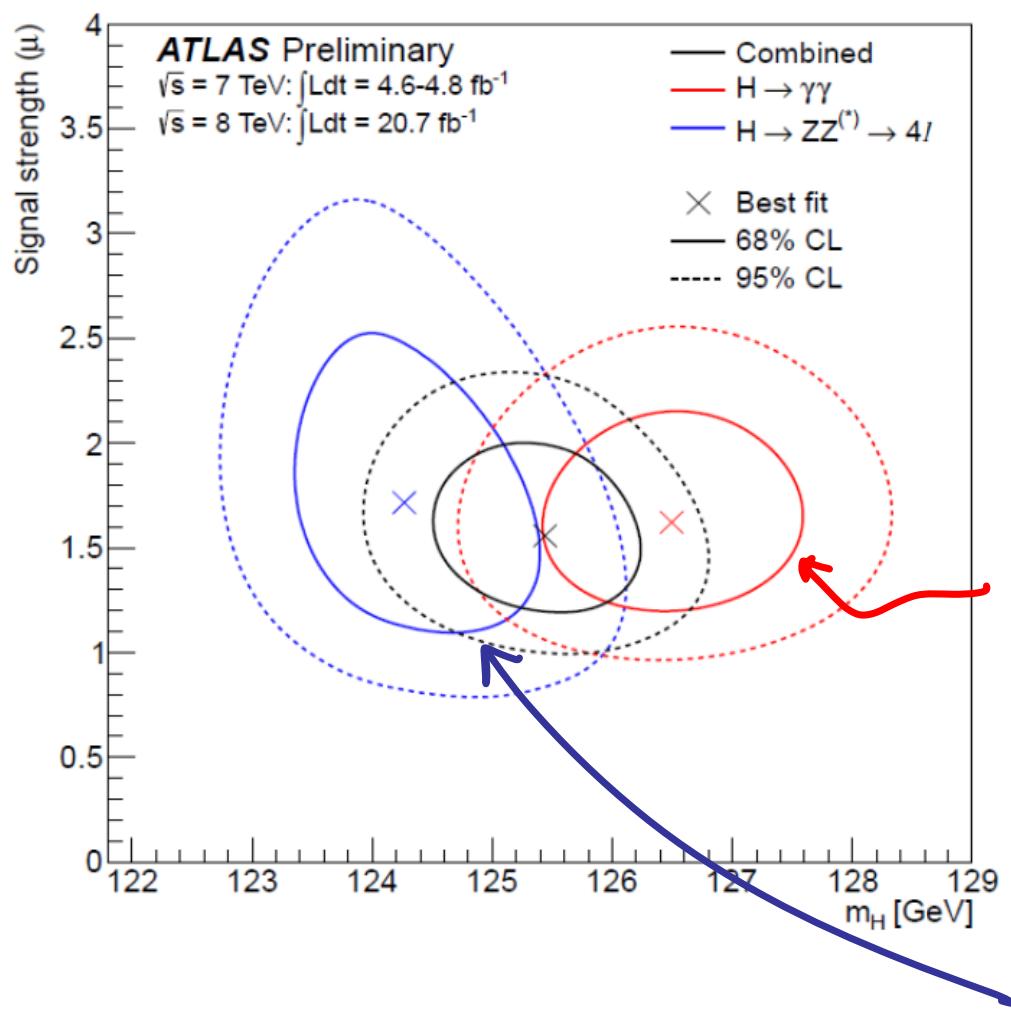
$125.5 + 0.2 \text{ (stat)} + 0.5/-0.6 \text{ (syst)}$

ATLAS-CONF-2013-14

$125.7 + 0.3 \text{ (stat)} + 0.3 \text{ (syst)}$

CMS-PAS-HIG-13-005

MASS DETERMINATION



HIGGS BOSON

h^0

$J^P = 0^+$

h^0 MASS

VALUE (GeV)

DOCUMENT ID

$125.5 + 0.2 \text{ (stat)} + 0.5/-0.6 \text{ (syst)}$

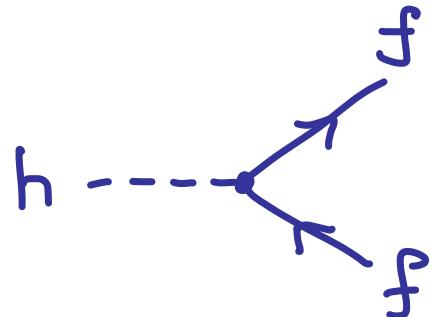
ATLAS-CONF-2013-14

$125.7 + 0.3 \text{ (stat)} + 0.3 \text{ (syst)}$

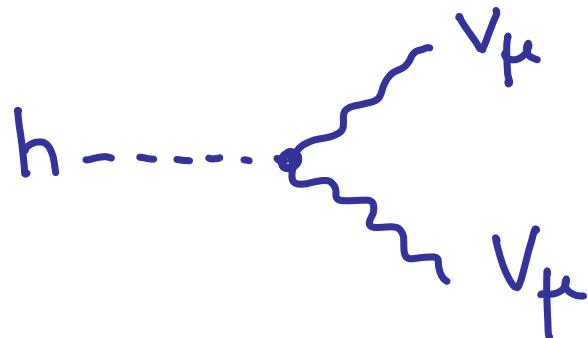
CMS-PAS-HIG-13-005

h^0 couplings

HIGGS COUPLINGS SEEN SO FAR

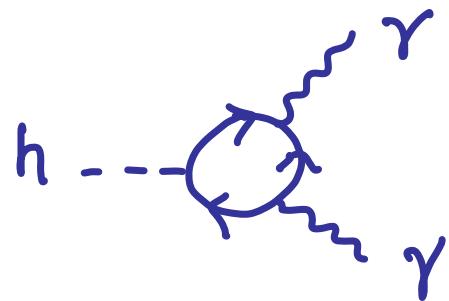
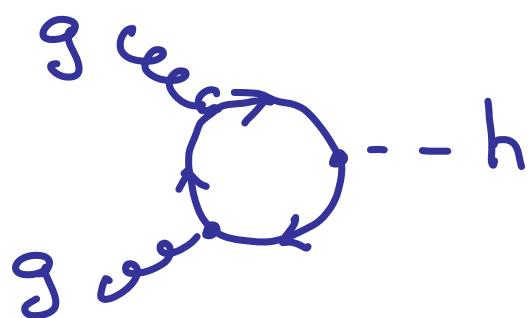


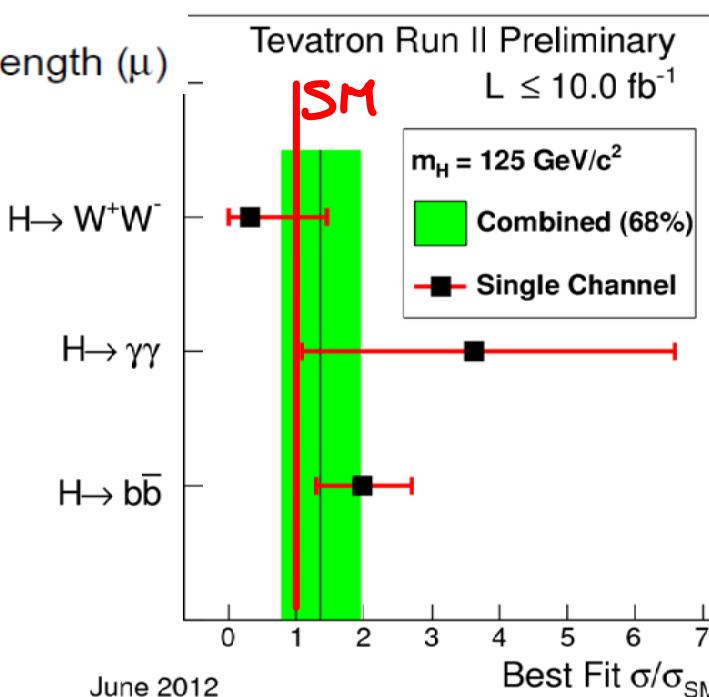
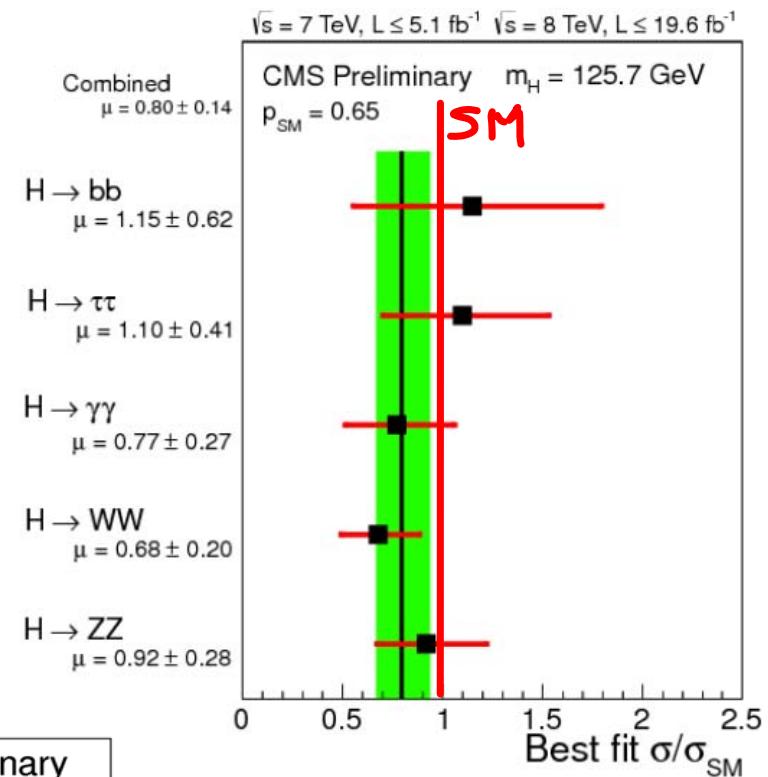
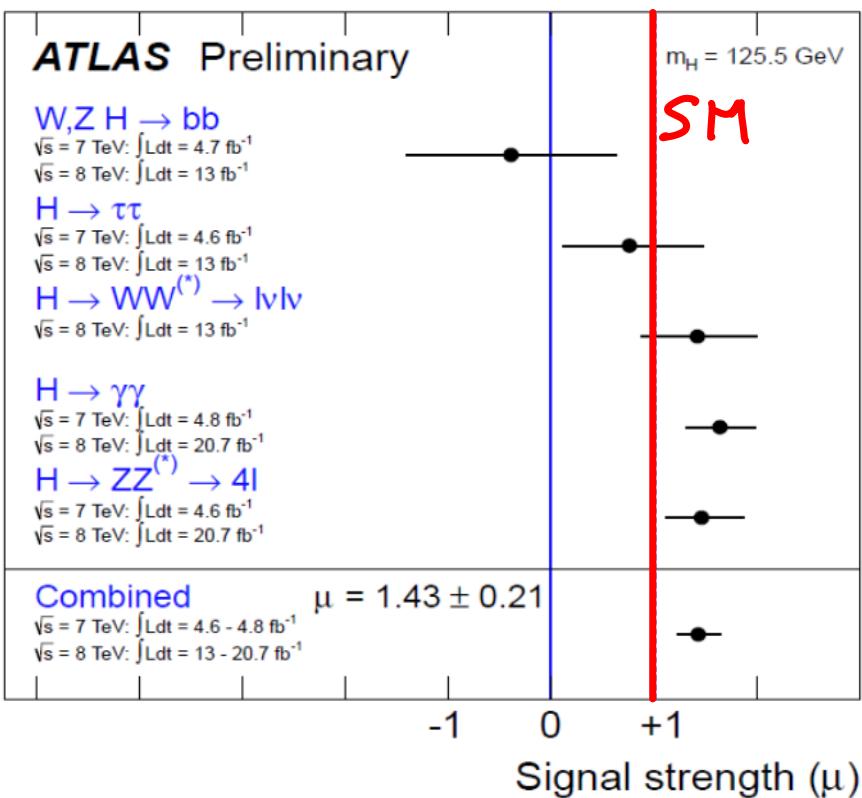
$$f = \begin{cases} \text{top (indirectly)} \\ \text{bottom} \\ \text{tau} \end{cases}$$



$$\nu_\mu = \begin{cases} w \\ z \end{cases}$$

LOOP INDUCED





Values close to SM-like .

But wait, The Higgs is no ordinary particle !

- * We're seeing the first non-gauge interactions
- * We might be seeing the first spin ϕ fundamental particle !
- * We want to learn about the mechanism behind electroweak symmetry breaking !
- * From that perspective, some quantities are more important than others:

Mass value Important

Determining J^P /Discarding $J=2$ Less so

Precise measurement of couplings Crucial

WHY COUPLINGS MATTER

SM Higgs sector is the less tested and more problematic



Affected by
hierarchy problem

Calls for
new physics at
the TeV scale

It's very likely that the Higgs will
depart from its SM properties

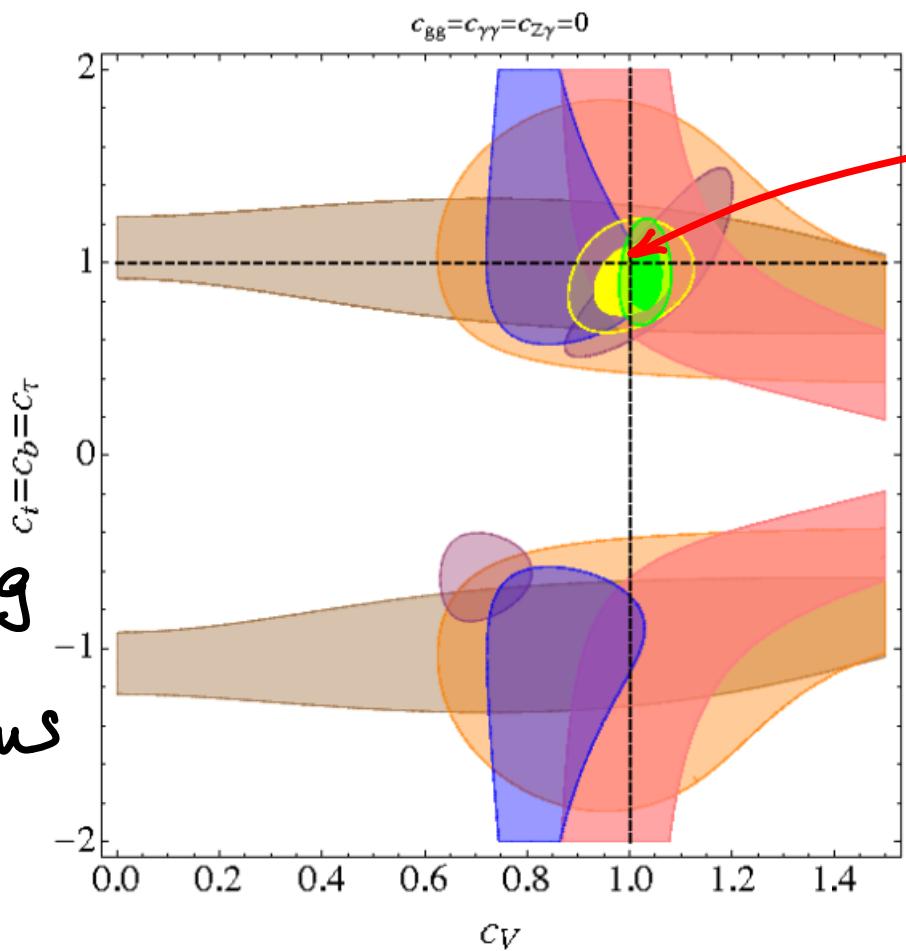
The importance of measuring Higgs couplings:
window to natural new physics

FITS, FITS, FITS

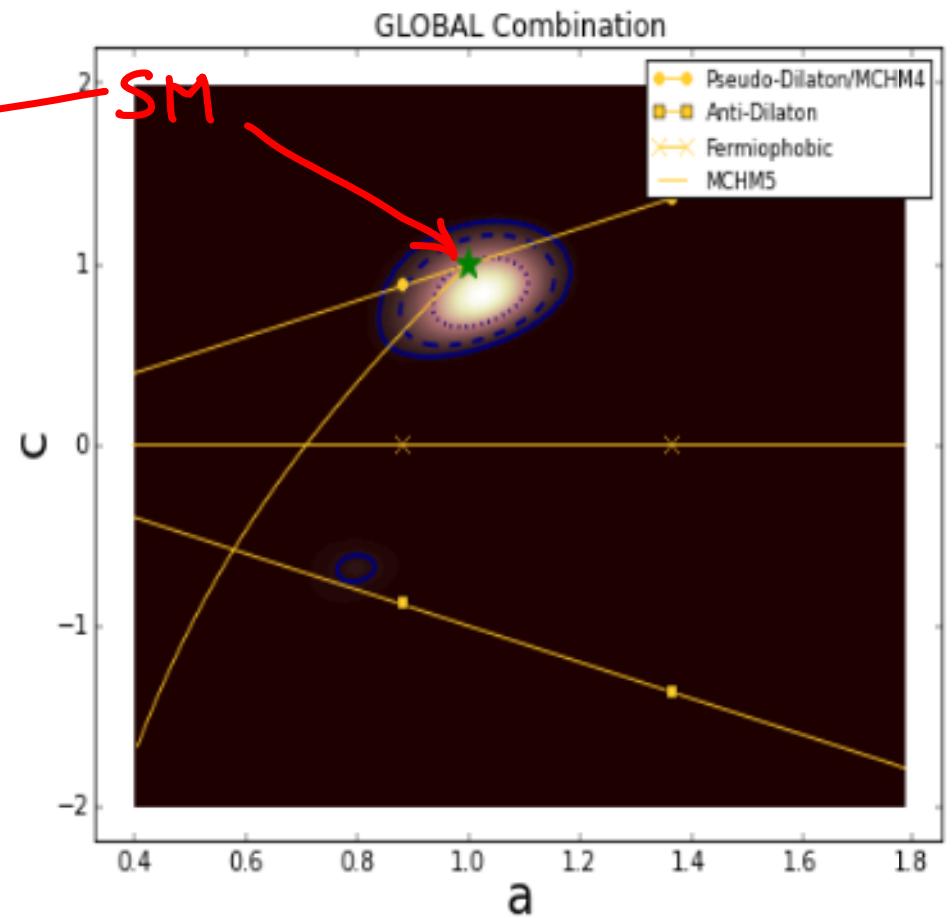
Falkowski, Riva, Urbano'13

Ellis, You '13

Coupling
to
fermions

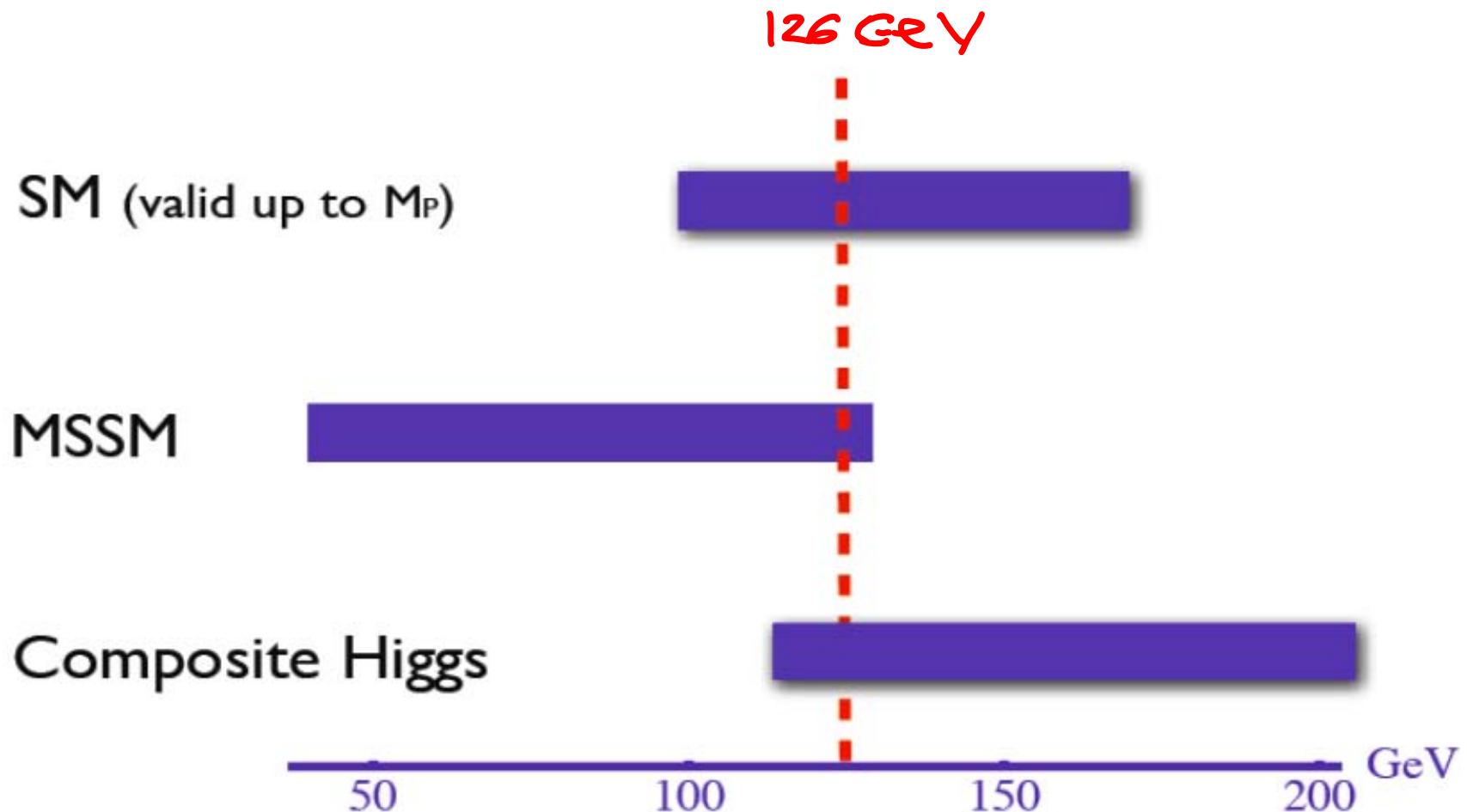


Coupling to gauge bosons



M_h AS MODEL DISCRIMINATOR

Higgs mass range



WARNING !

**YOU ARE LEAVING THE
NATURAL SECTOR**

**ВЫ ВЫЕЗЖАЕТЕ ИЗ
ПРИРОДНОГО СЕКТОРА**

**VOUS SORTEZ DU
SECTEUR NATUREL**

SIE VERLASSEN DEN NATÜRLICHEN SEKTOR

$M_H \approx 126$ GeV. IMPLICATIONS FOR STABILITY

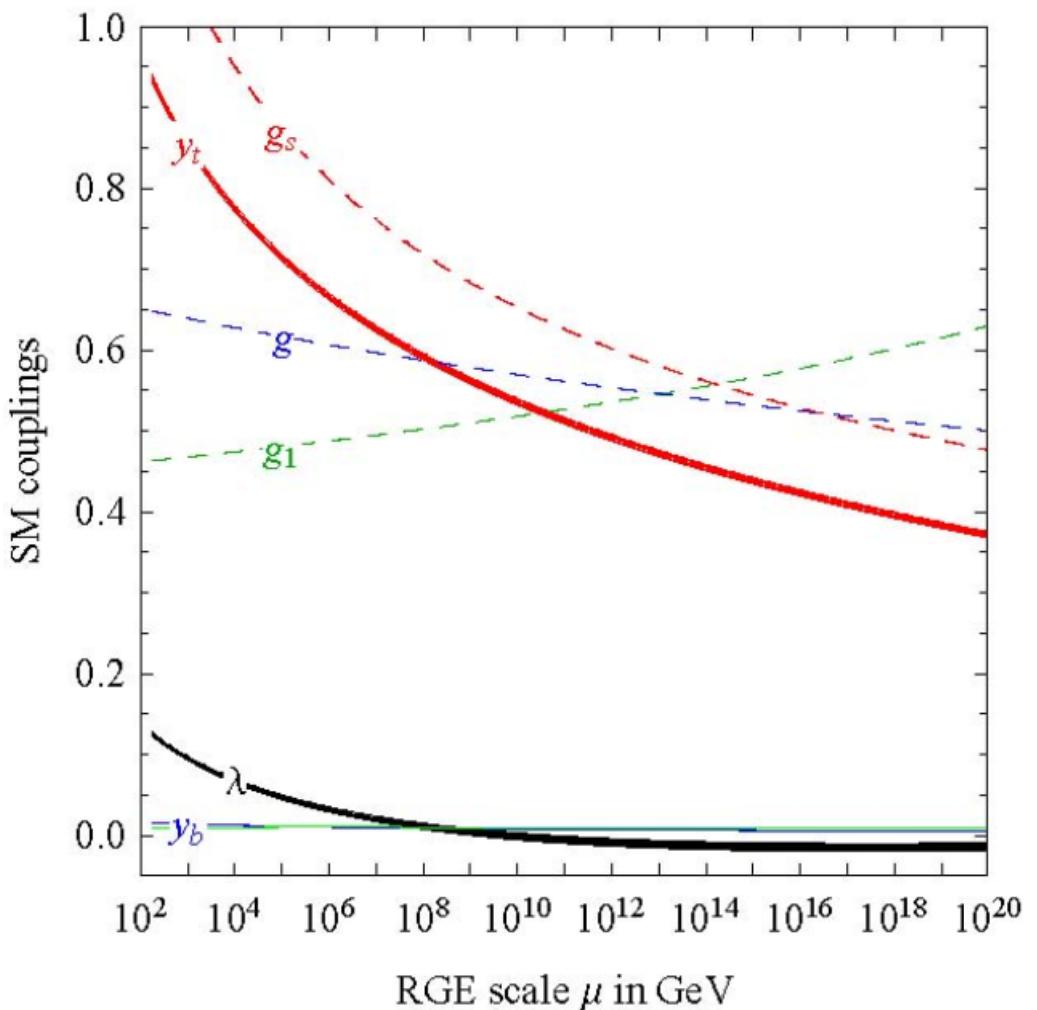
Assume Higgs has SM props. and no BSM Physics

All SM parameters known

$$M_h \rightarrow \lambda(\epsilon_w)$$

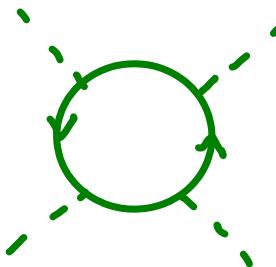
forgetting naturalness, can
the pure SM be valid
up to M_{Pl} ?

Weakly coupled up to M_{Pl}



VACUUM INSTABILITY

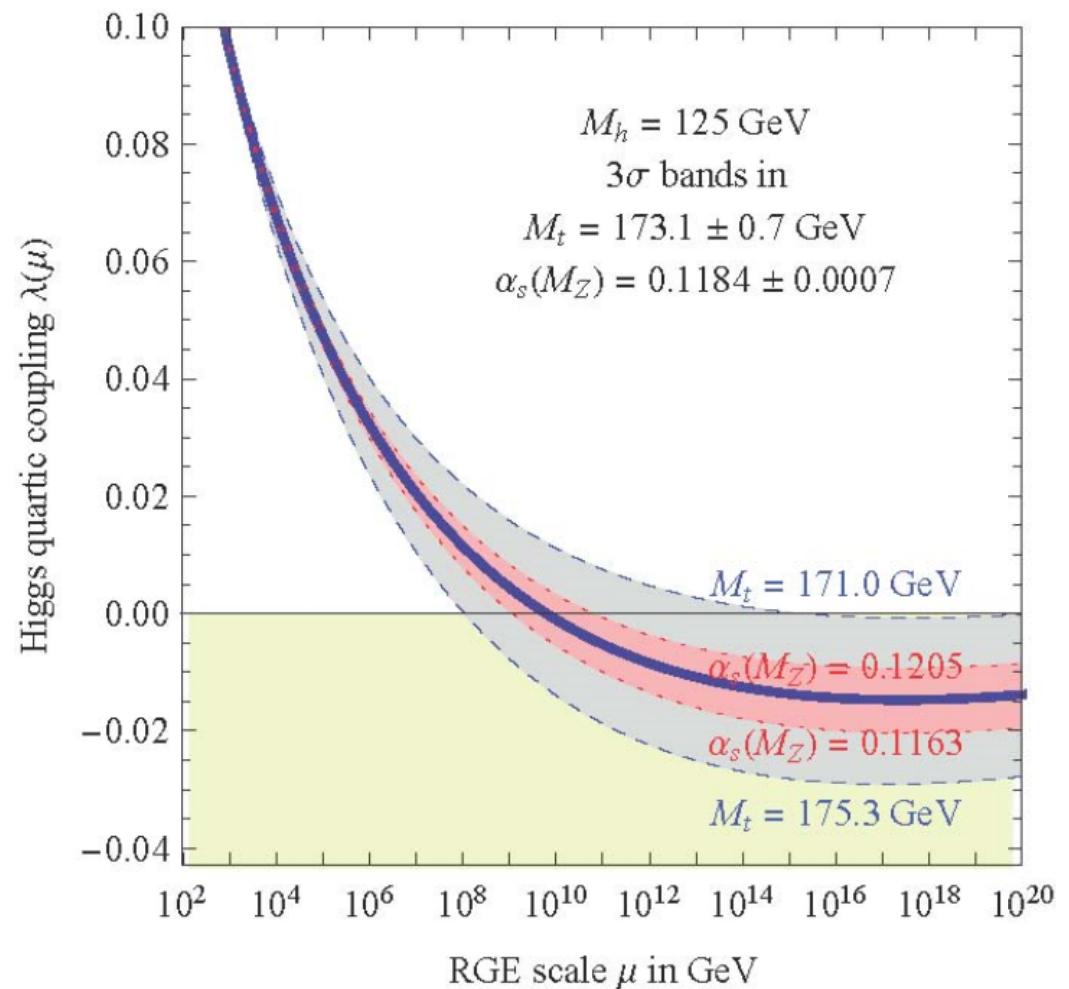
$$\frac{d\lambda}{d\ln Q} \sim -\frac{h_t^4}{16\pi^2}$$



$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

↓
Higgs potential instability

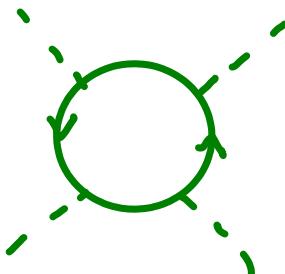
$$V(\phi \gg M_t) \approx \frac{1}{4} \lambda(Q \approx h) h^4$$



cabibbo et al'79, Hung'79, Lindner'86

VACUUM INSTABILITY

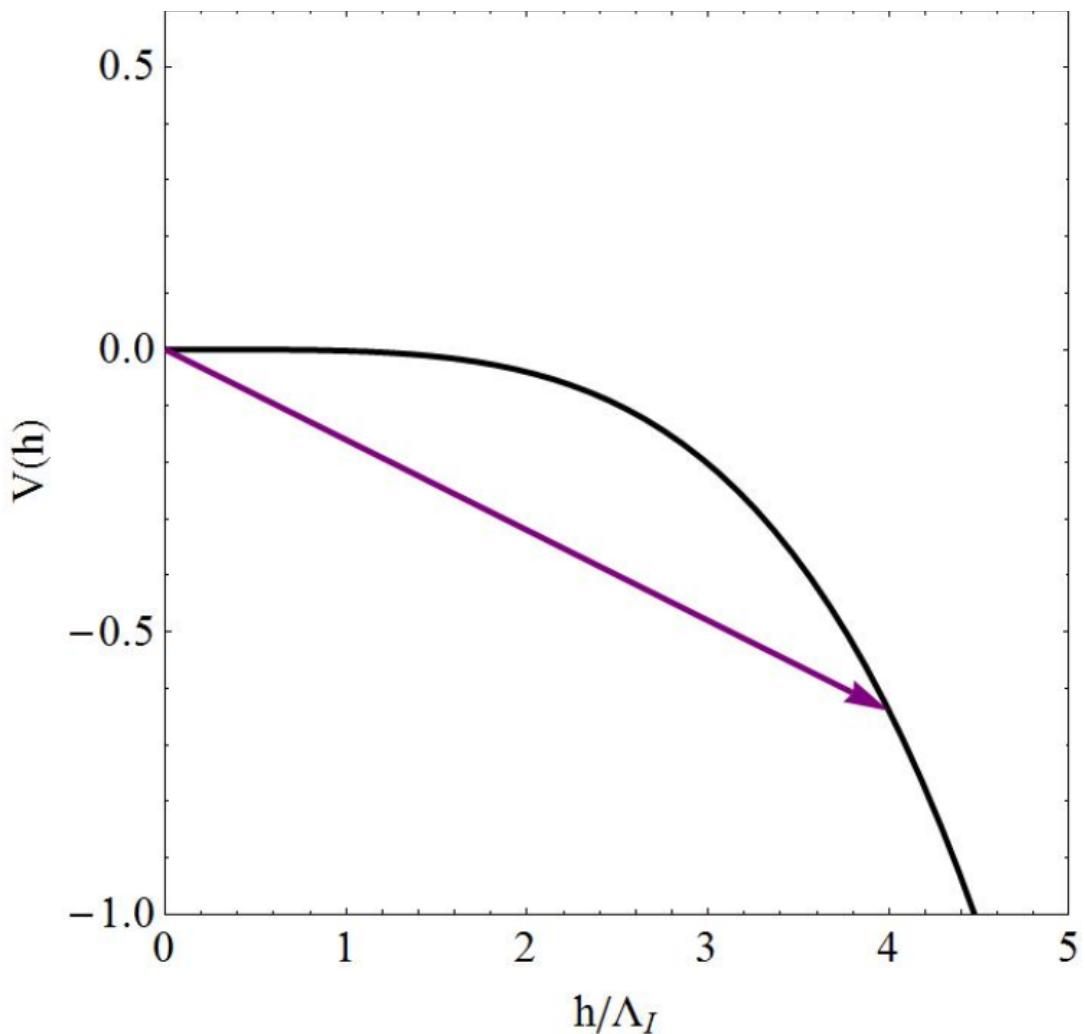
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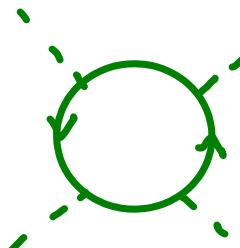
Higgs potential instability

$$V(\phi \gg M_t) \simeq \frac{1}{4} \lambda(Q \approx h) h^4$$



VACUUM INSTABILITY

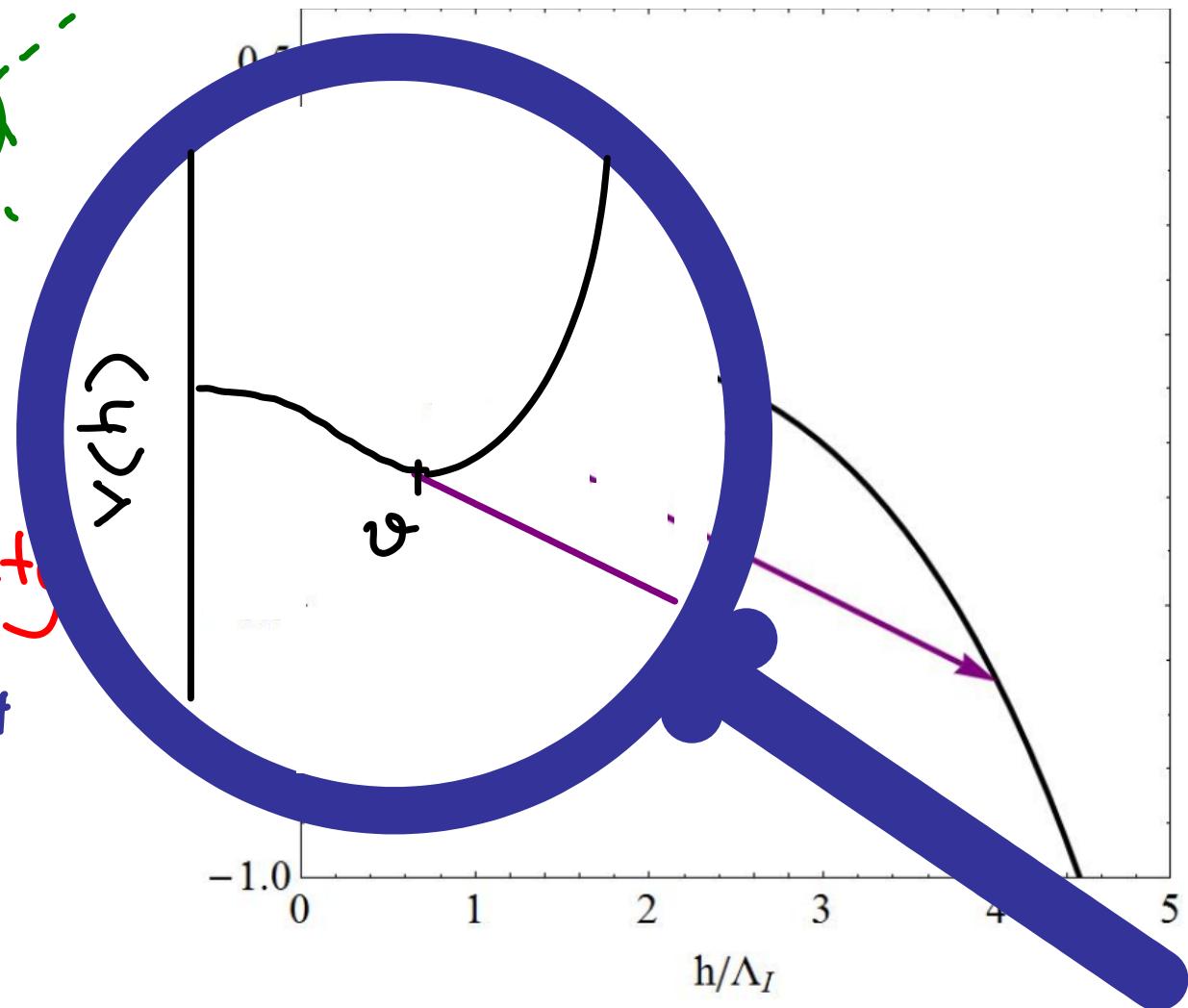
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Higgs potential instability

$$V(\phi \gg M_t) \simeq \frac{1}{4} \lambda(Q \approx h) h^4$$



LIFE IN A METASTABLE VACUUM

$$p = \text{Decay prob.} = \underbrace{\frac{\text{Decay rate}}{\Delta t \cdot \Delta V}}_{h^4 e^{-S_4}} \tau_0^4 \quad \text{with} \quad \tau_0^4 \sim (e^{140}/M_{Pl})^4$$

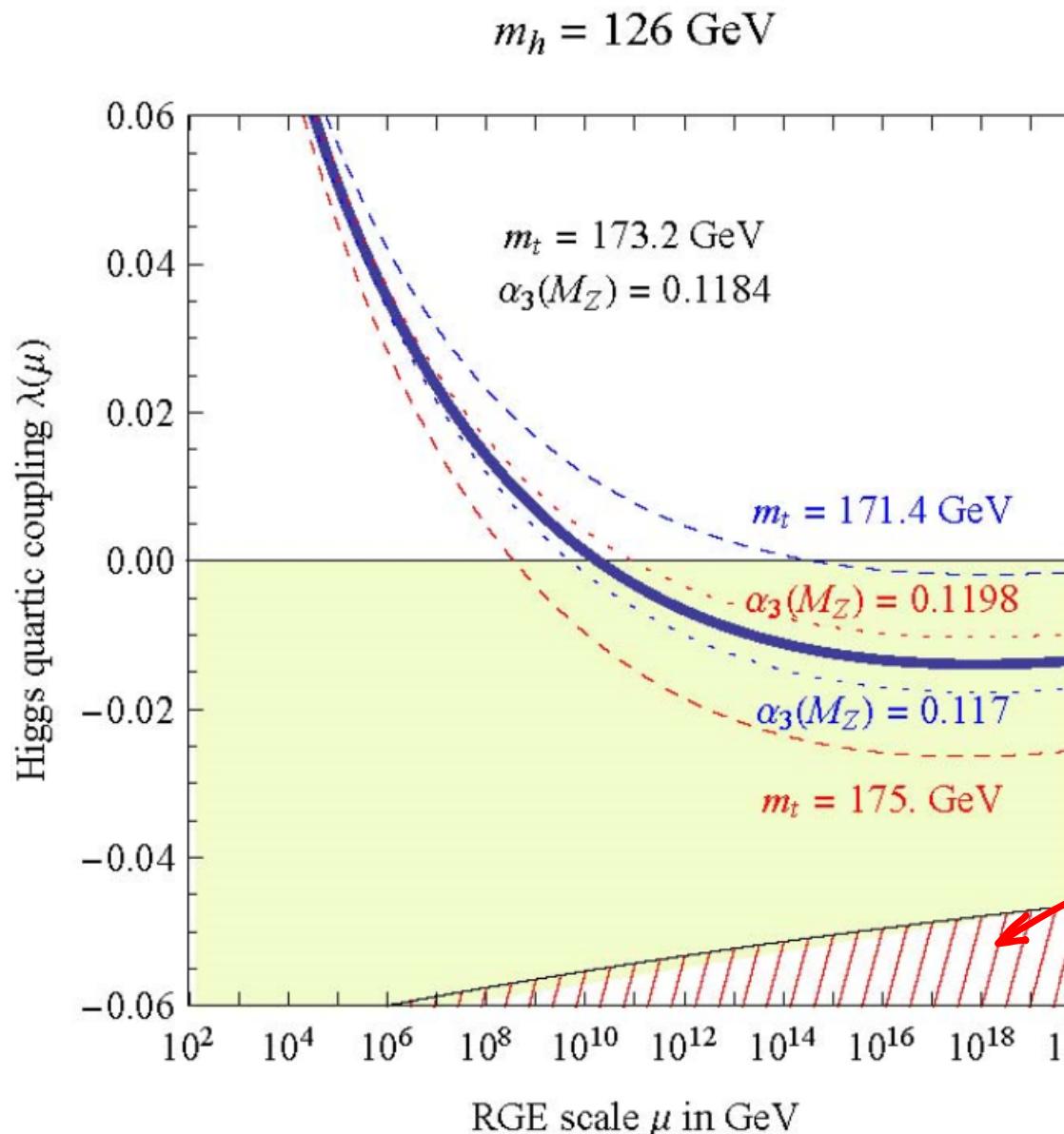
$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|21/0.01|}\right]$$

easily wins over τ_0^4

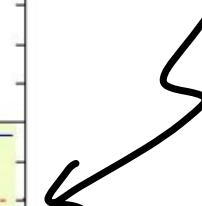
$p \ll 1$: Lifetime of EW vacuum much longer than τ_0

Typical value $\tau_0 \sim 10^{100}$ yrs.

LIFE IN A METASTABLE VACUUM

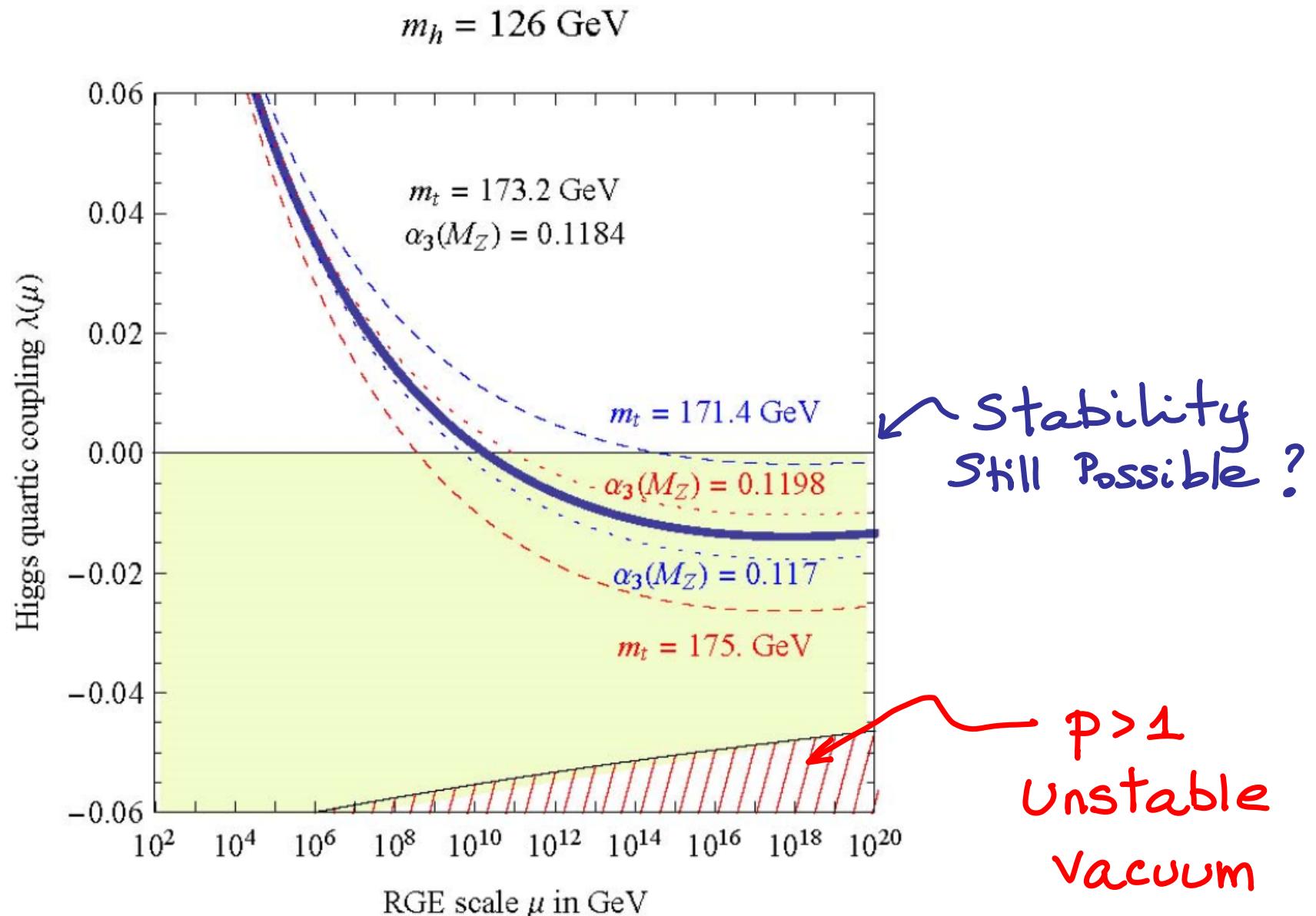


Lifetime $\propto \exp \frac{1}{|\lambda|}$
 $\gg \text{age of Universe}$



$p > 1$
Unstable
vacuum

LIFE IN A METASTABLE VACUUM



NNLO STABILITY BOUND

For stability up to M_{Pl} :

$$M_h [\text{GeV}] > 129.4 + 1.4 \left(\frac{M_t (\text{GeV}) - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right)^{\pm 1.0_{\text{th}}}$$

State-of-the-art NNLO calculation:

- 2-loop V_{eff} (Ford, Jack, Jones [hep-ph/0111190])
- 3-loop RGES (... Chetyrkin, Zoller [hep-ph/1205.2892])
- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$
(... Shaposhnikov et al [hep-ph/1205.2893],
, Degrassi et al [hep-ph/1205.6497])

Reduces theory error by a factor 3

TOP MASS CAVEATS

Have assumed

$$M_t = 173.1 \pm 0.7 \text{ GeV}$$

from Tevatron + LHC is the top pole mass.

Theoretically cleaner determination from $\sigma(t\bar{t})$
but larger error

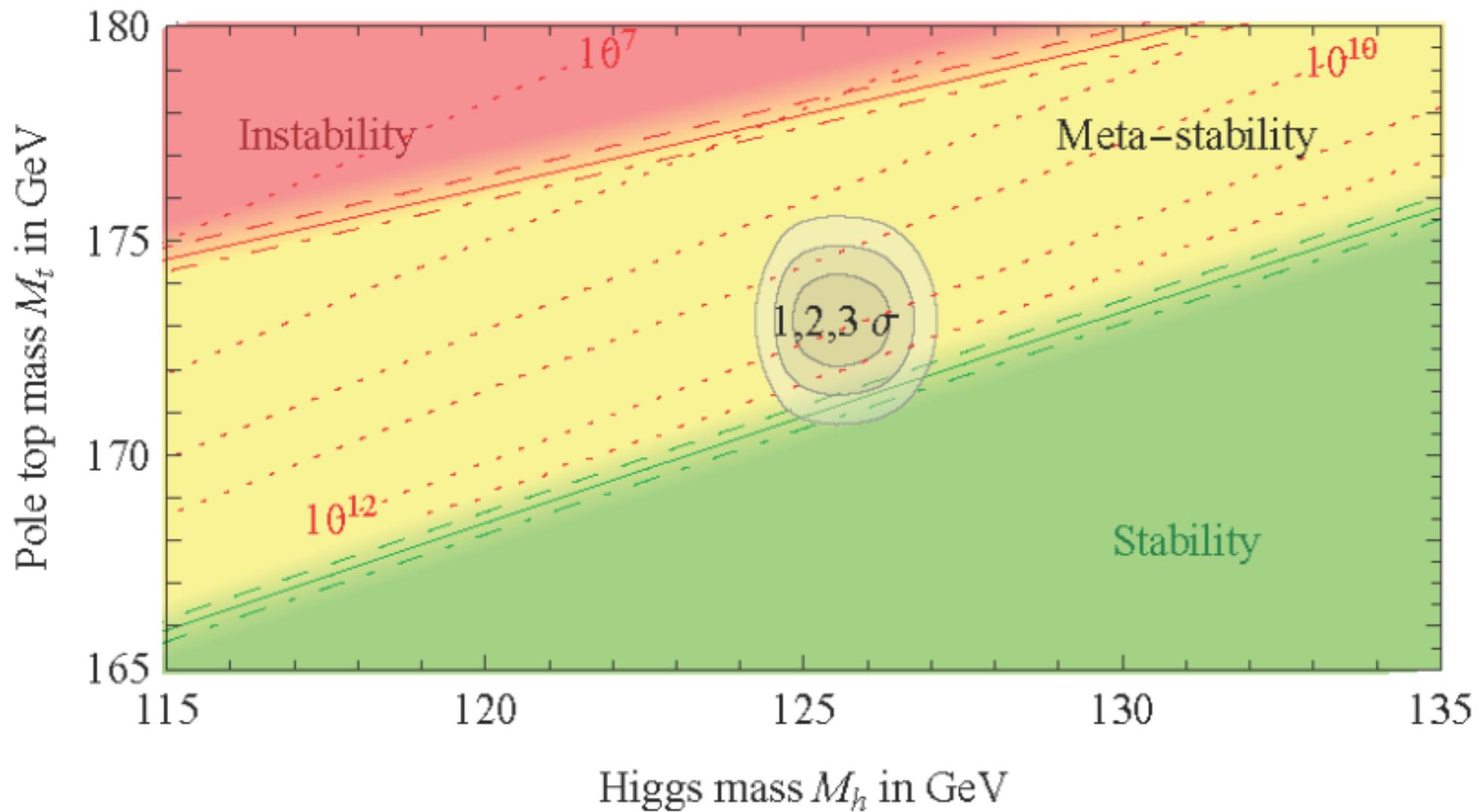
$$M_t = 173.3 \pm 2.8 \text{ GeV}$$

would still allow for stability

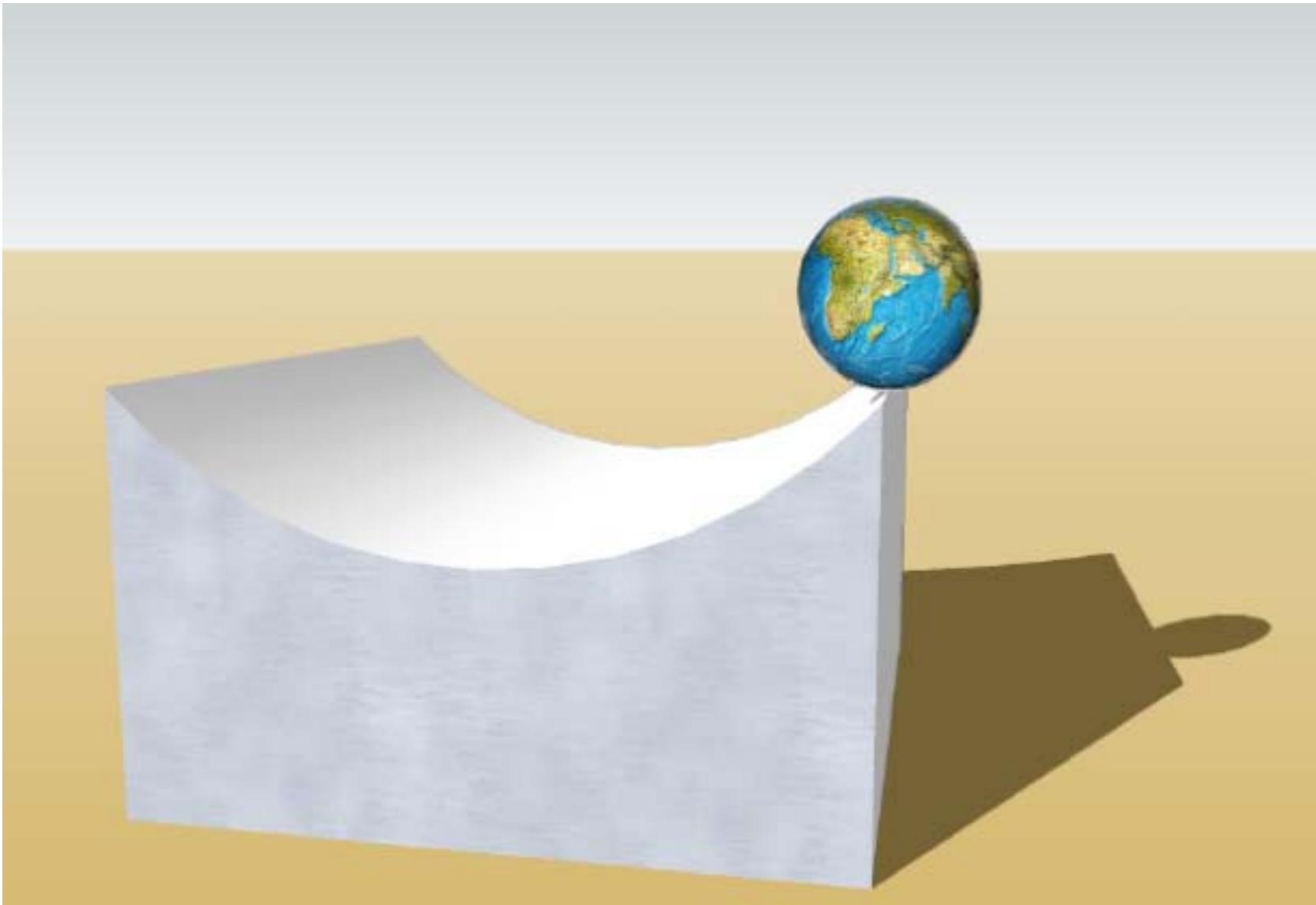
Alekhin, Djouadi, Moch'12

Too conservative given the good agreement...

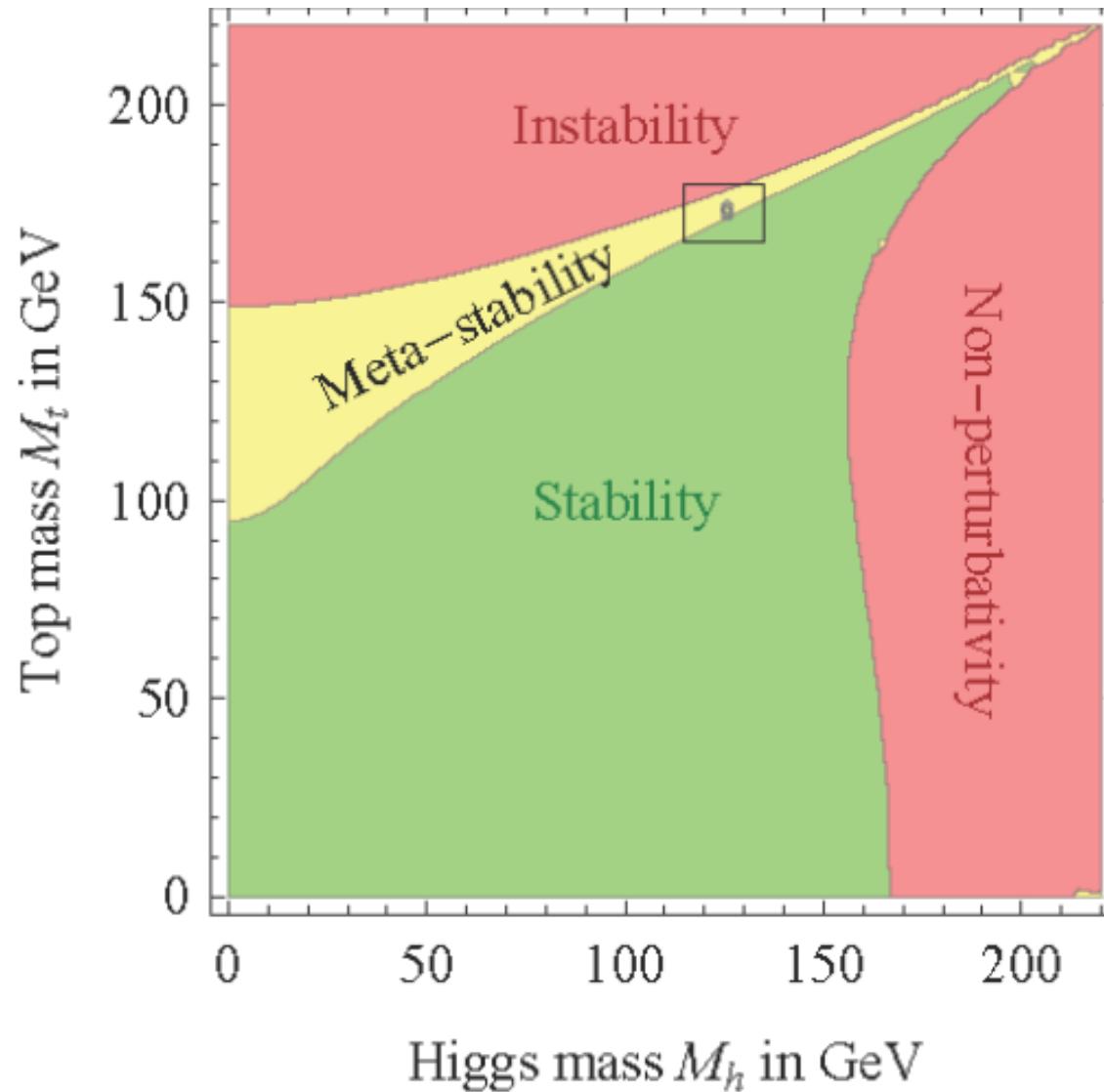
LIVING AT THE EDGE



LIVING AT THE EDGE



LIVING AT THE EDGE

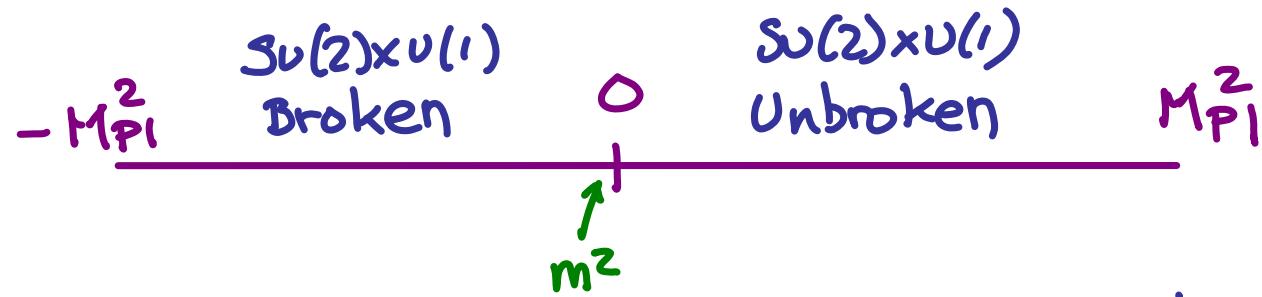


NEW KNOWLEDGE BRINGS NEW QUESTIONS

- ★ Why do we live near the critical boundary for stability?

$$\lambda(M_{Pl}) \approx 0$$

- ★ Is this related to our living near the phase boundary $m^2/M_{Pl}^2 \approx 0$?



- ★ Is the EW scale determined by Planck scale physics?
- ★ Or is this just a coincidence? BSM...

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

IRRELEVANT

MAKE IT WORSE

CURE IT

BSM & STABILITY

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Example

IRRELEVANT

See-saw neutrinos

MAKE IT WORSE

CURE IT

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BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

Example

IRRELEVANT

See-saw neutrinos

$$M_R \lesssim 10^{13} \text{ GeV}$$

MAKE IT WORSE

See-saw neutrinos

$$M_R \gtrsim 10^{13} \text{ GeV}$$

CURE IT

See-saw neutrinos

$$M_R \sim \langle S \rangle \quad \& \quad \lambda_{HS} |H|^2 |S|^2$$

BSM IMPLICATIONS

- See-saw neutrinos: Impact on $\beta_2 = -y_\nu^4/(16\pi^2) \ast$

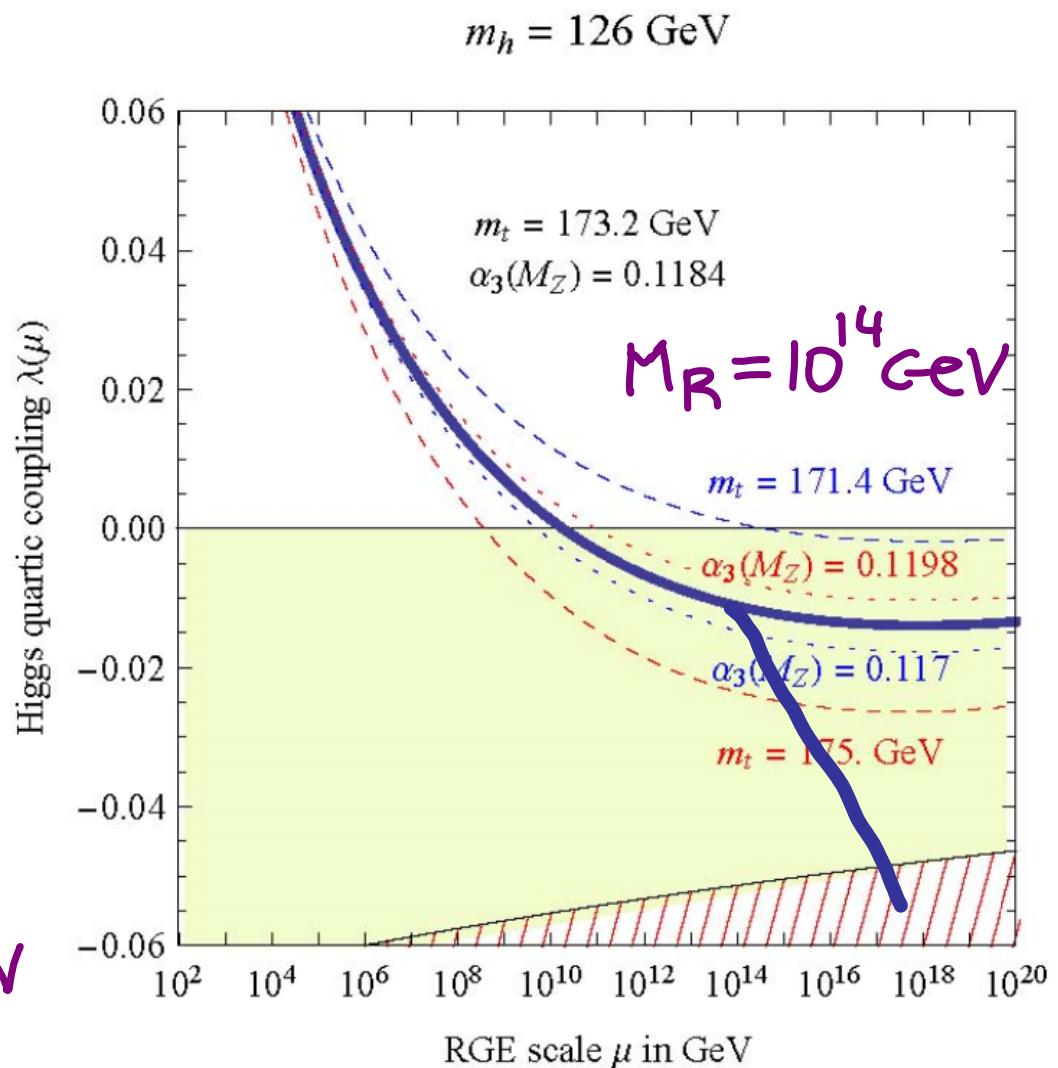
$$m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$

$$M_R \uparrow \Leftrightarrow y_\nu \uparrow$$



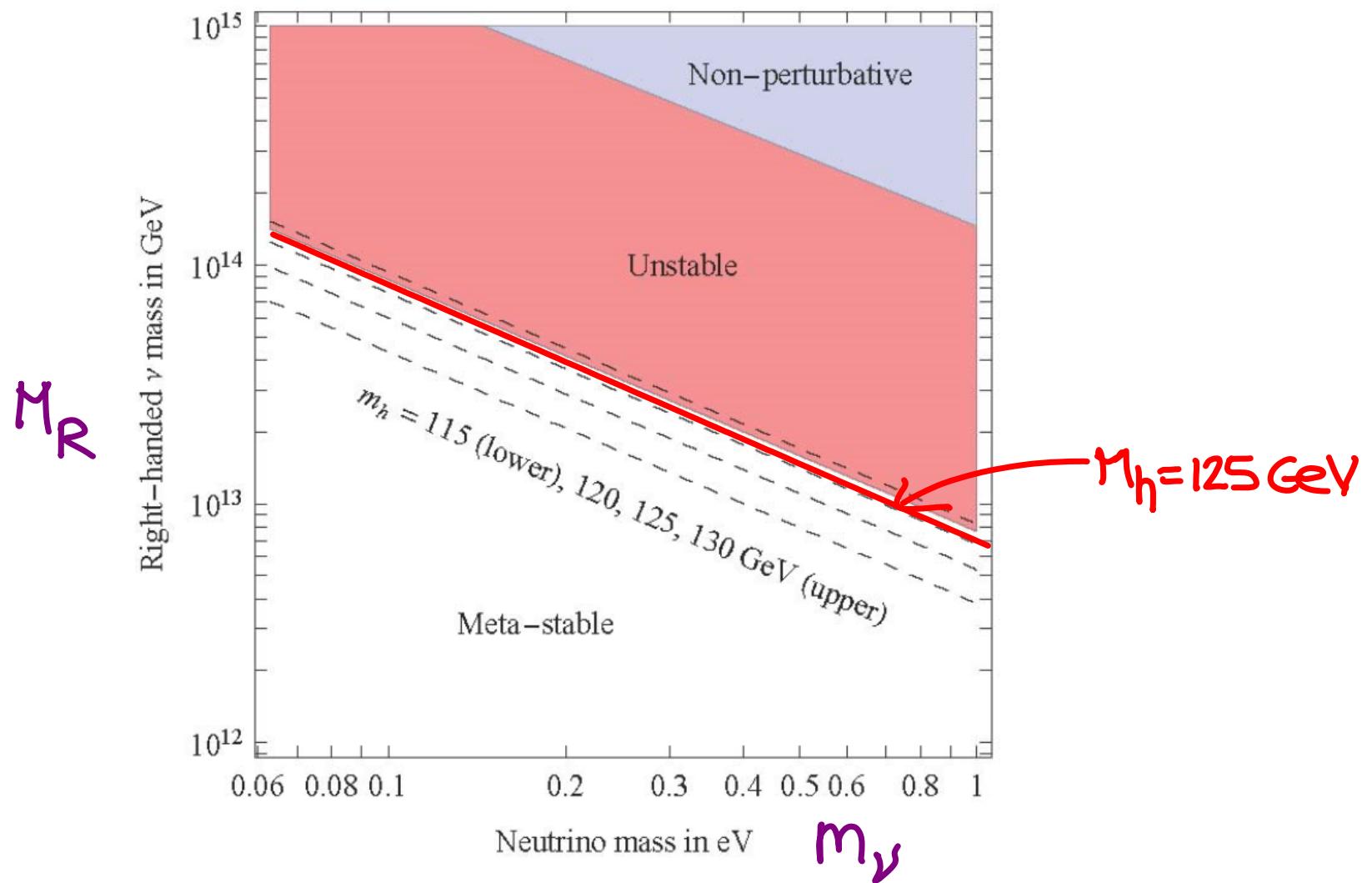
Adds to the top destabilizing effect

Important for $M_R \gtrsim 10^{13-14} \text{ GeV}$



BSM IMPLICATIONS

- See-saw neutrinos : Bound on $M_{\nu R}$



SIMPLE VACUUM STABILIZATION

J.Elias-Miró , JRE, G.F.Giudice, H.M. Lee , A. Strumia '12
See also D. Lebedev '12

Ingredients :

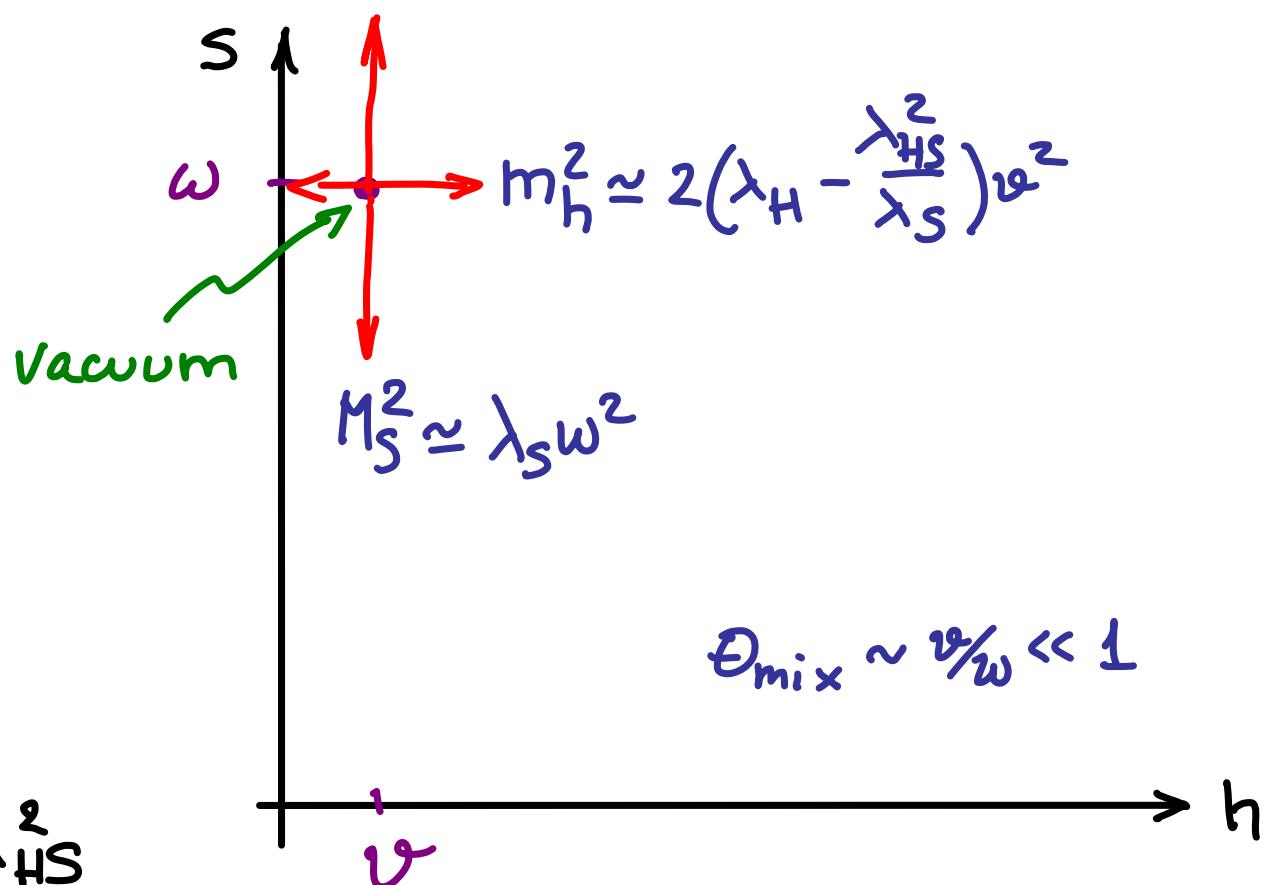
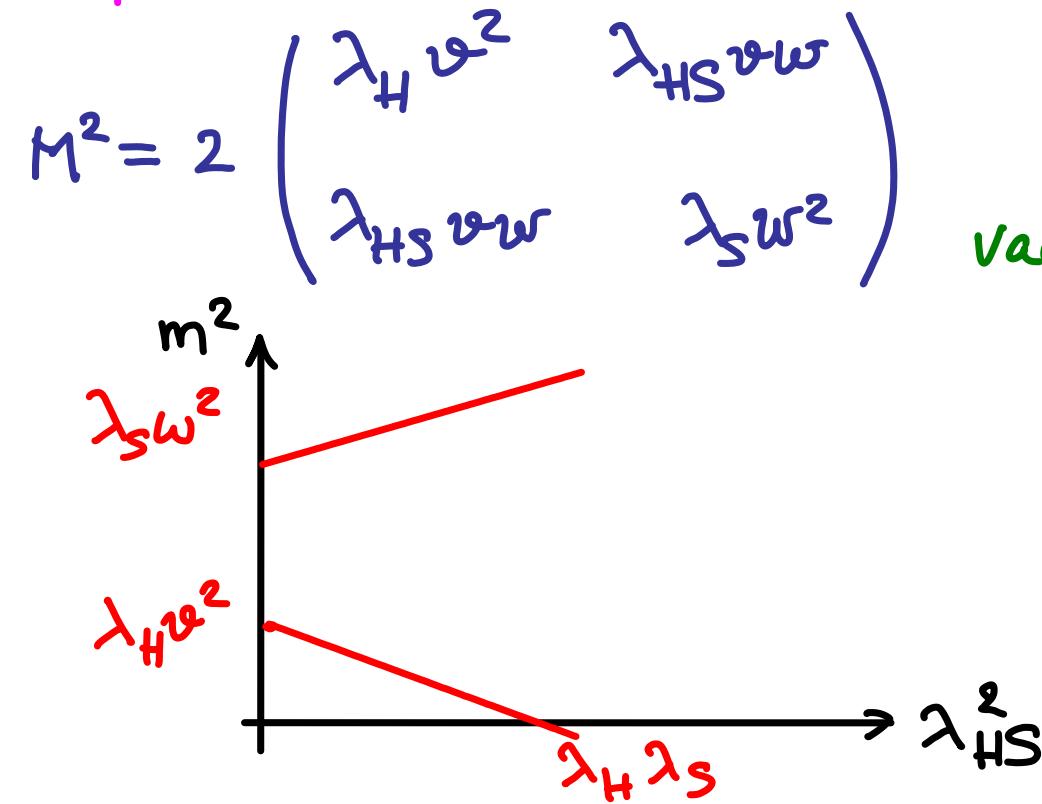
- One extra scalar singlet S
- below the instability scale Λ_I
- coupled to the Higgs like $\lambda_{HS} |H|^2 S^+ S^-$
- with non-zero vev : $\langle S \rangle = w \neq 0$
(we will assume $w \gg v$)

MODEL STRUCTURE

Potential:

$$V = \lambda_H (|H|^2 - v^2/2)^2 + \lambda_S (S^+ S - \omega^2/2)^2 + 2 \lambda_{HS} (|H|^2 - v^2/2)(S^+ S - \omega^2/2)$$

Spectrum:



LOW-ENERGY THEORY

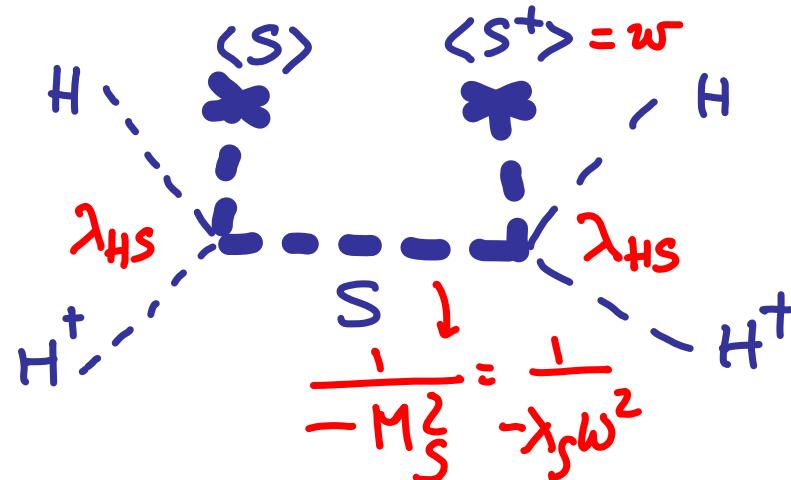
Integrating out $S \not\rightarrow$ Below M_S : SM

$$V(h) = \lambda (|H|^2 - v^2/2)^2$$

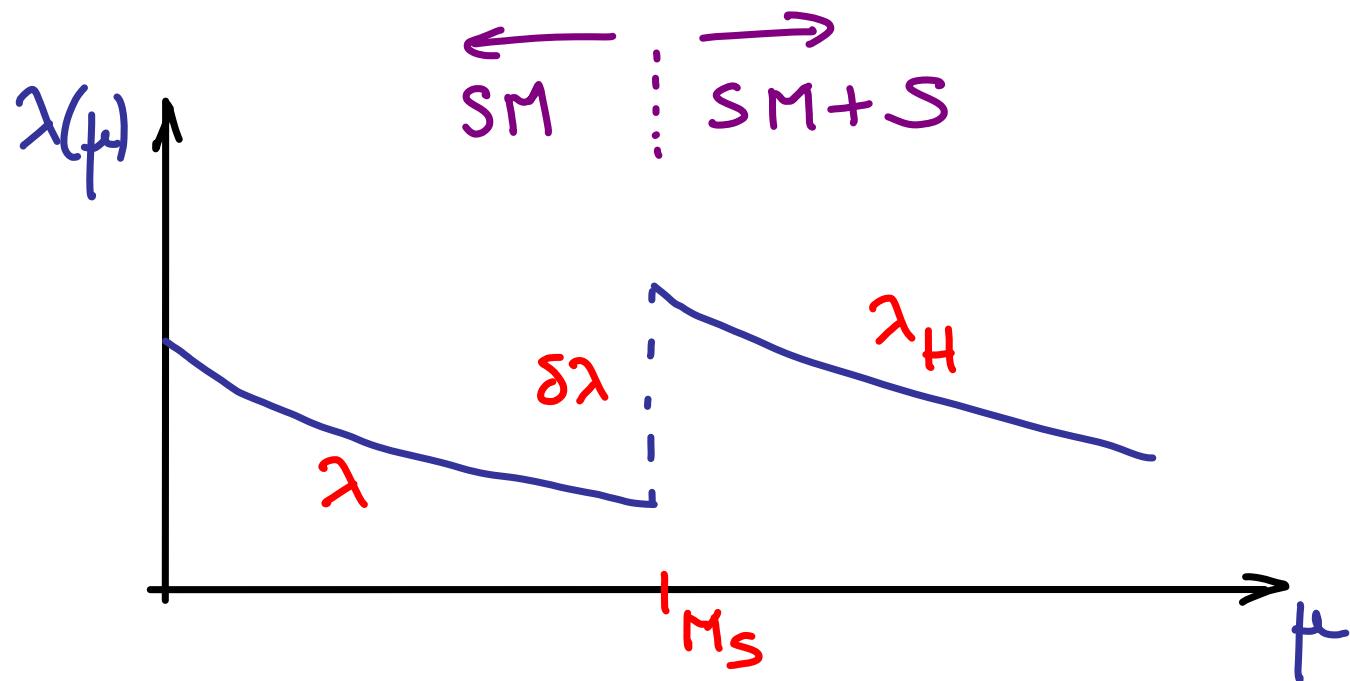
$$\lambda_H - \underbrace{\frac{\lambda_{HS}}{\lambda_S}}_{\text{tree-level threshold correction}}$$

\sim original
 h quartic

Diagrammatically



CRUCIAL THRESHOLD CORRECTION



Matching at M_S : $\lambda(M_S) = \lambda_H(M_S) - \delta\lambda$

$\delta\lambda$ has the right sign to improve stability

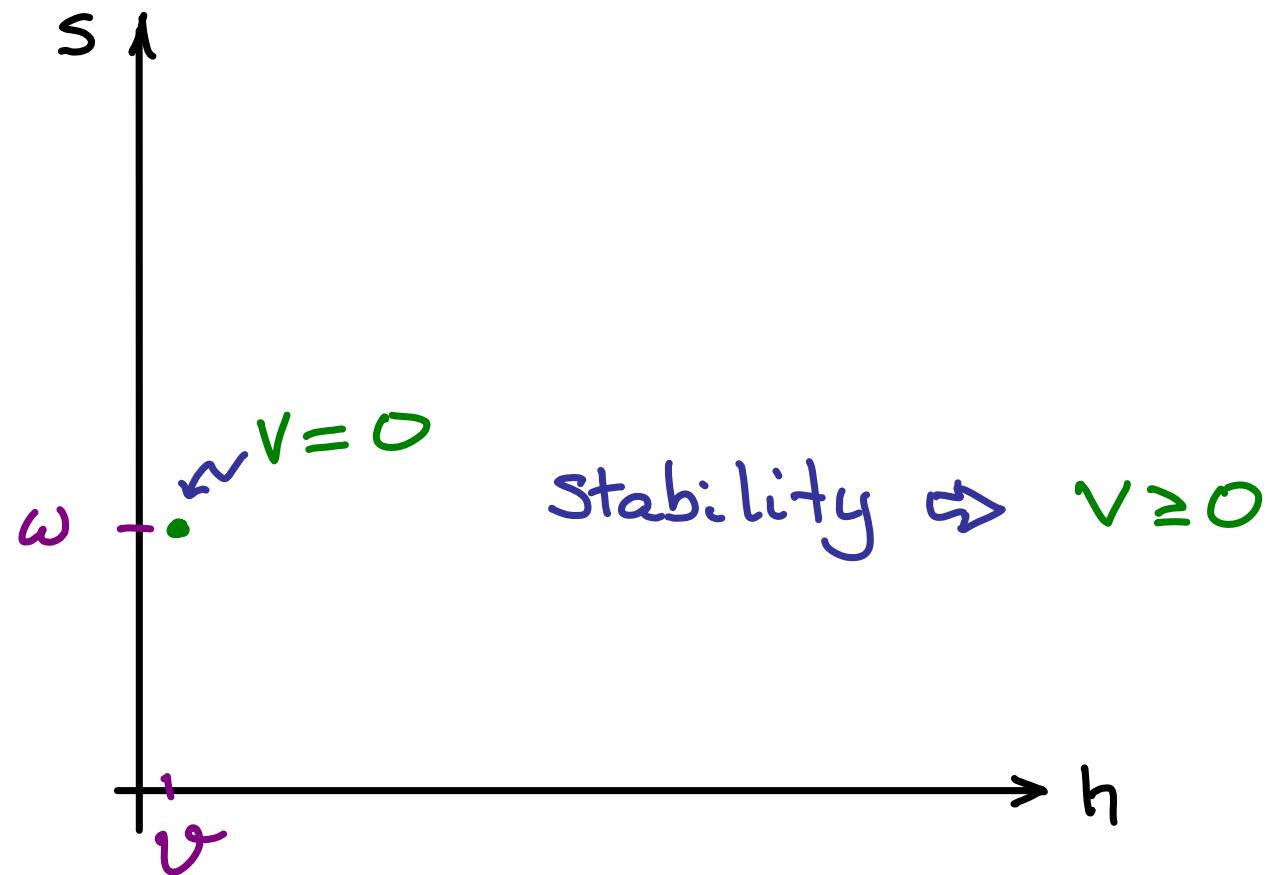
CRUCIAL THRESHOLD CORRECTION



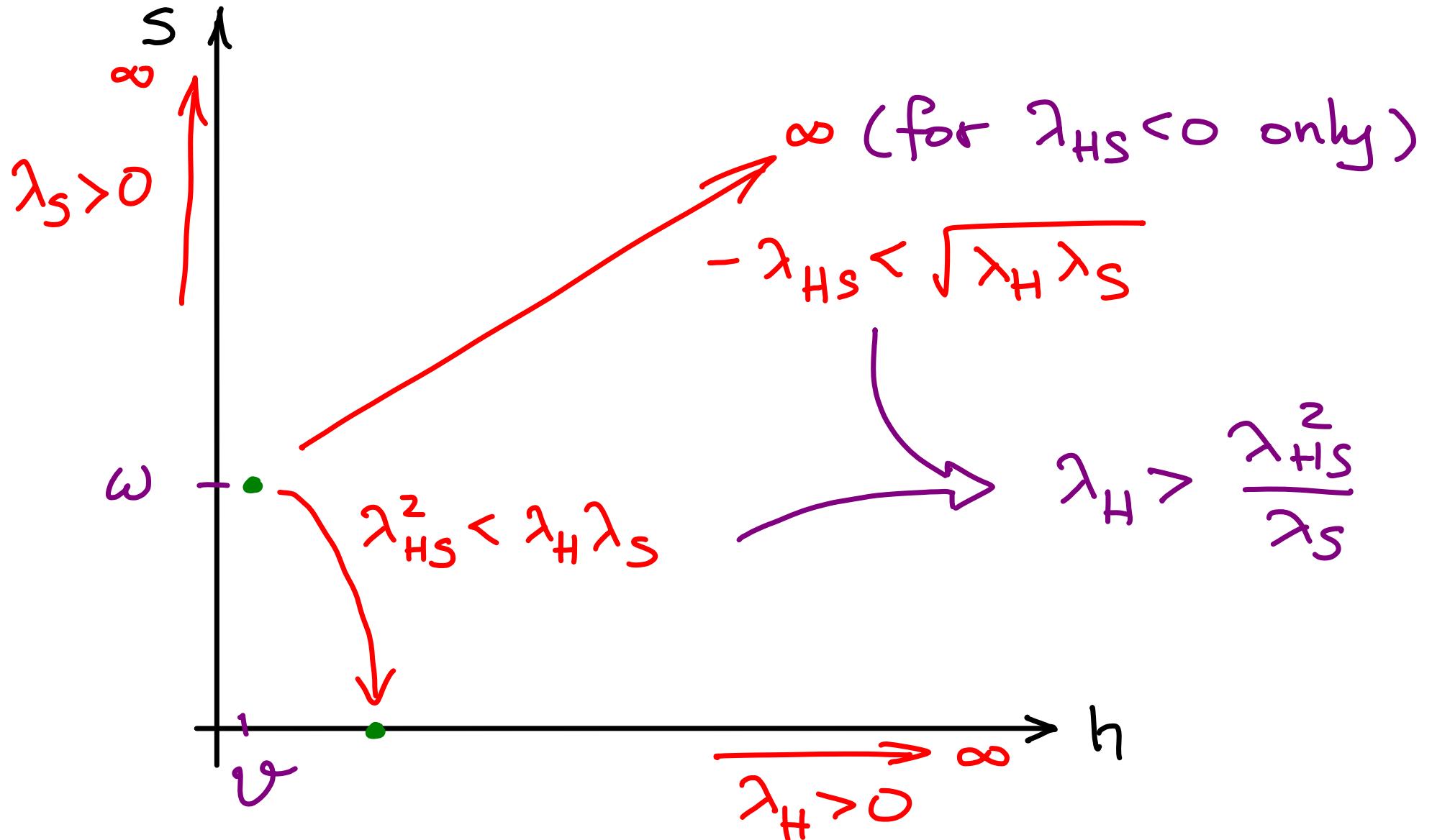
$\delta\lambda$ has the right sign to improve stability
But, we must look more closely to stab. conditions.

STABILITY CONDITIONS

$$V = \lambda_H (|H|^2 - \omega^2/2)^2 + \lambda_S (S^+ S - \omega^2/2)^2 + 2 \lambda_{HS} (|H|^2 - \omega^2/2)(S^+ S - \omega^2/2)$$



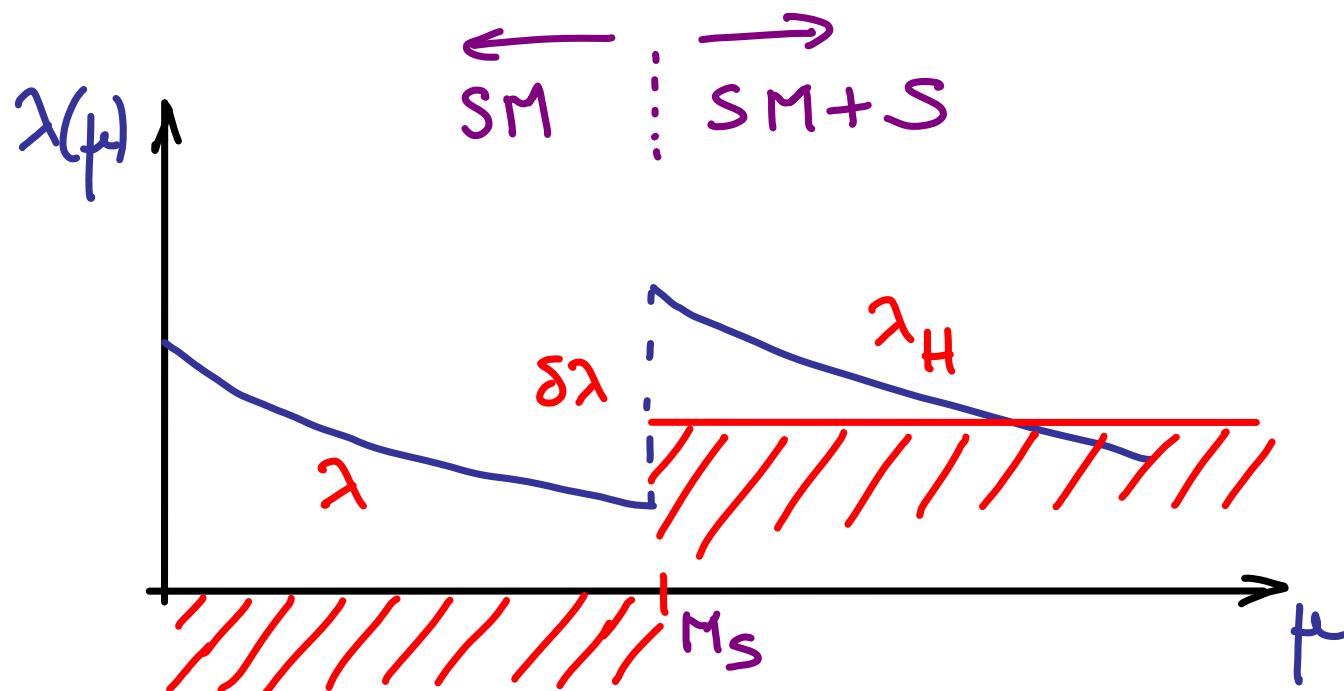
STABILITY CONDITIONS



CRUCIAL THRESHOLD CORRECTION

Stability condition $\lambda_H > \frac{\lambda_{HS}^2}{\lambda_S} = \delta\lambda$ shifted up

by same amount as λ ! No gain ??

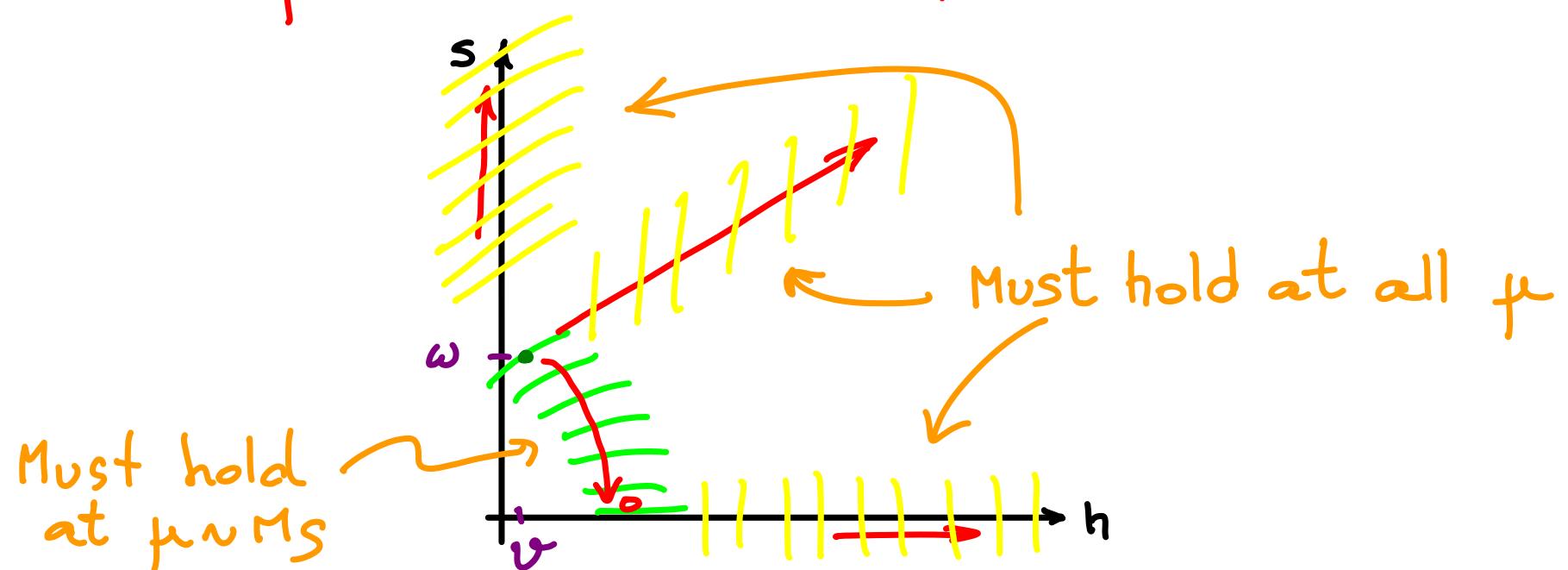


CRUCIAL THRESHOLD CORRECTION

Stability condition $\lambda_H > \frac{\lambda_{HS}^2}{\lambda_S} = \delta \lambda$ shifted up

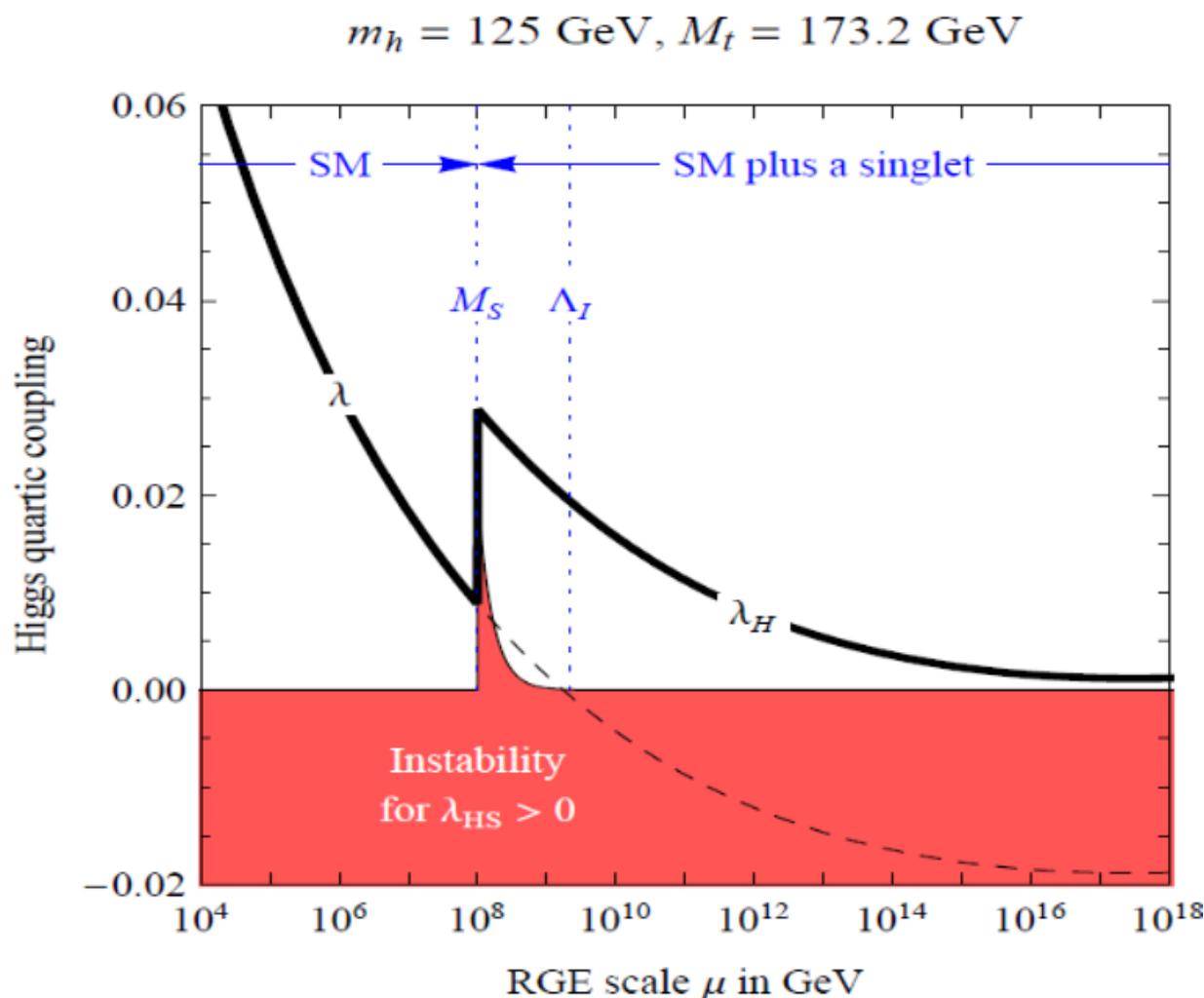
by same amount as λ ! No gain ??

Scale-dependence is all-important in stab. conditions



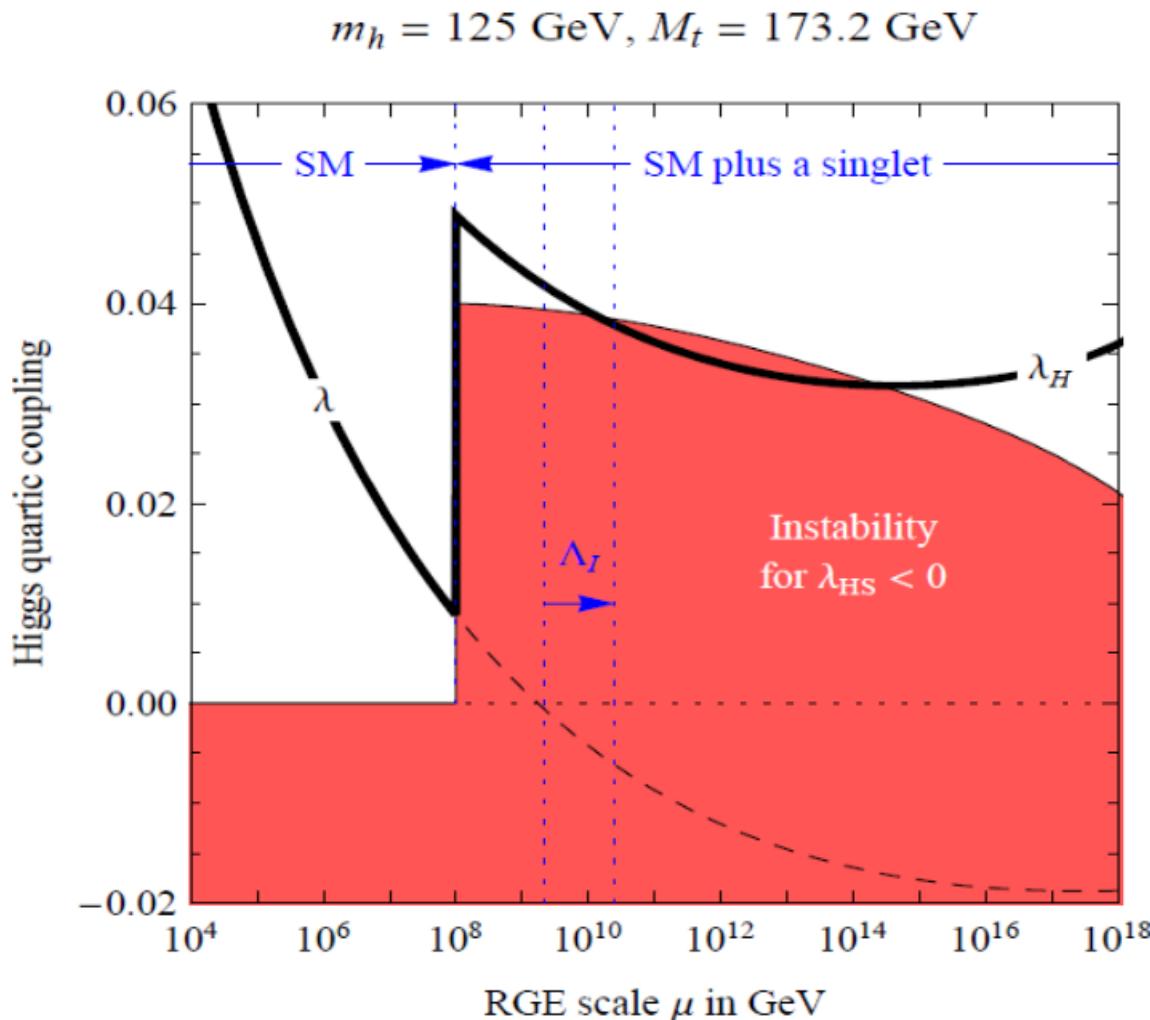
$$\lambda_{HS} > 0$$

Need to enforce $\lambda_H > \lambda_{HS}^2 / \lambda_S$ only at low-energy
for $f_e \sim M_S$

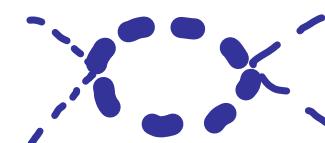


$$\lambda_{HS} < 0$$

Need to enforce $\lambda_H > \lambda_{HS}^2 / \lambda_S$ for all μ



Effect now relies
on loop effect

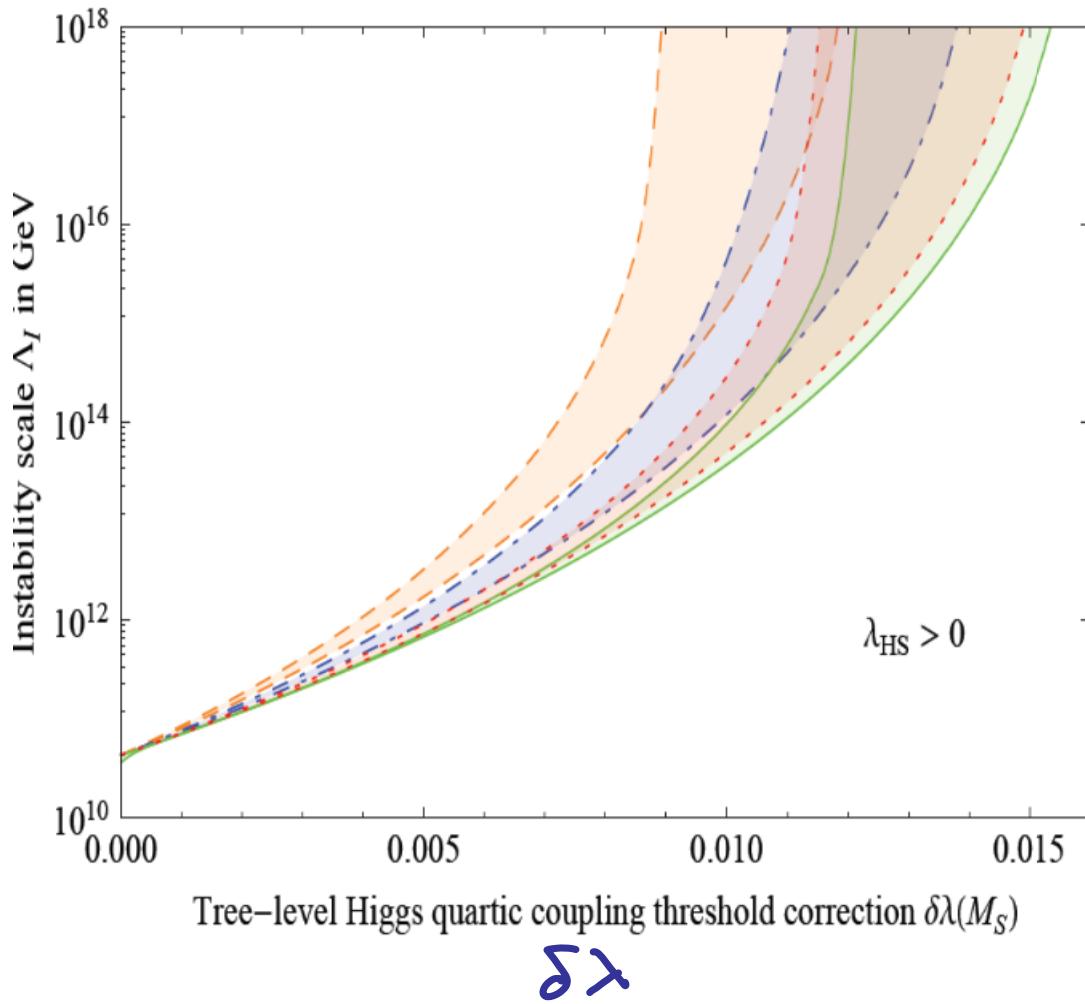


$$\delta\beta_{\lambda_H} = 4\lambda_{HS}^2 + 24\lambda_H^2$$

IMPACT ON INSTABILITY SCALE

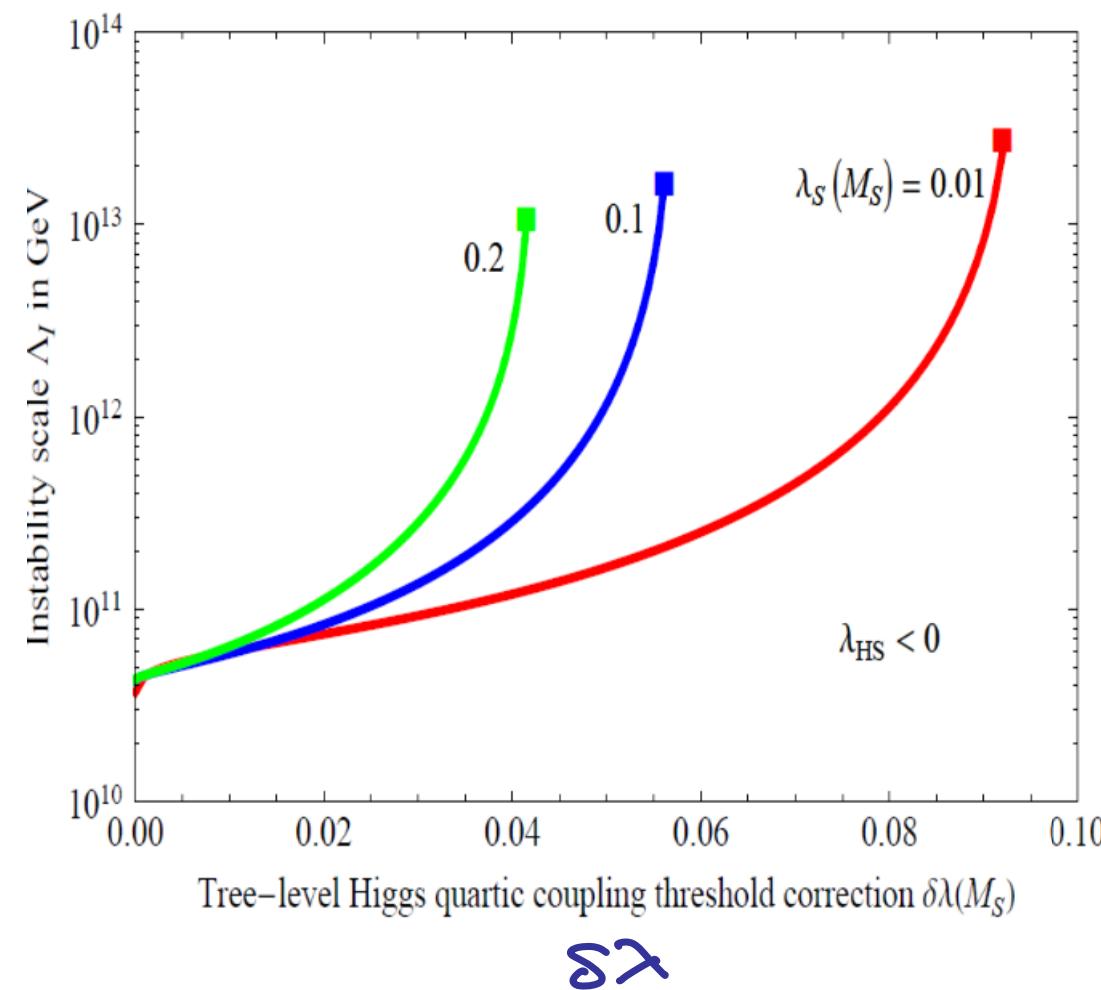
$\lambda_{HS} > 0$

$m_h = 125 \text{ GeV}$



$\lambda_{HS} < 0$

$m_h = 125 \text{ GeV}, M_S = 10^8 \text{ GeV}$



IMPLEMENTATION IN MODELS

In our paper :

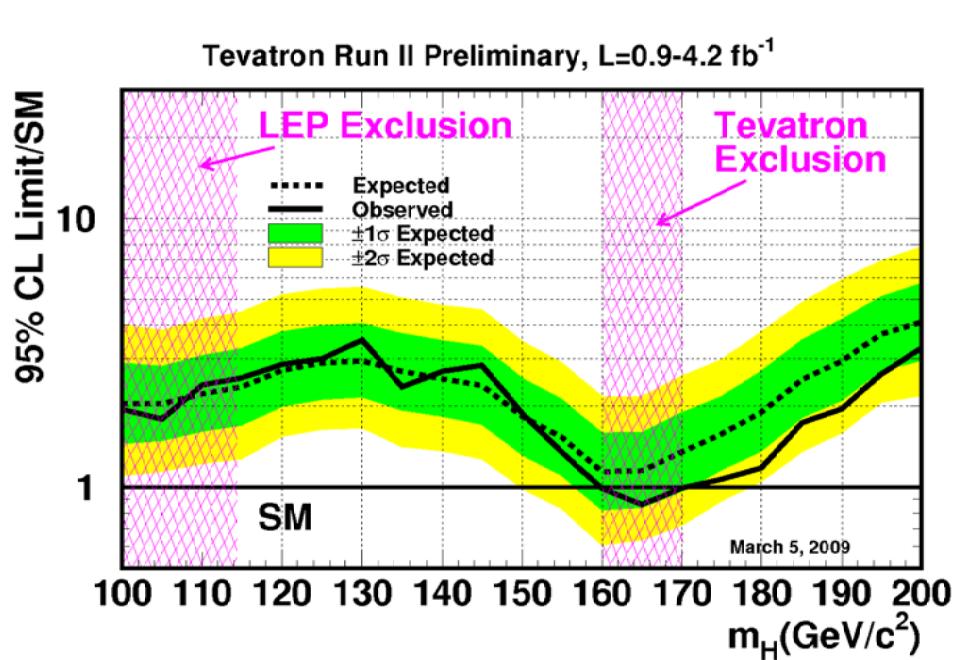
- See-saw neutrinos
- Invisible axion
- Singlet - unitarized Higgs inflation (Givice-Lee)

Later uses of the idea

- Non-commutative SM Chamseddine, Connes '12
- SM++ (a string-based extension of the SM)
Anchordoqui, Antoniadis et al '12
- "Higgs portal" scenarios (with $\lambda_{HS} |H|^2 S^2$)
Several...

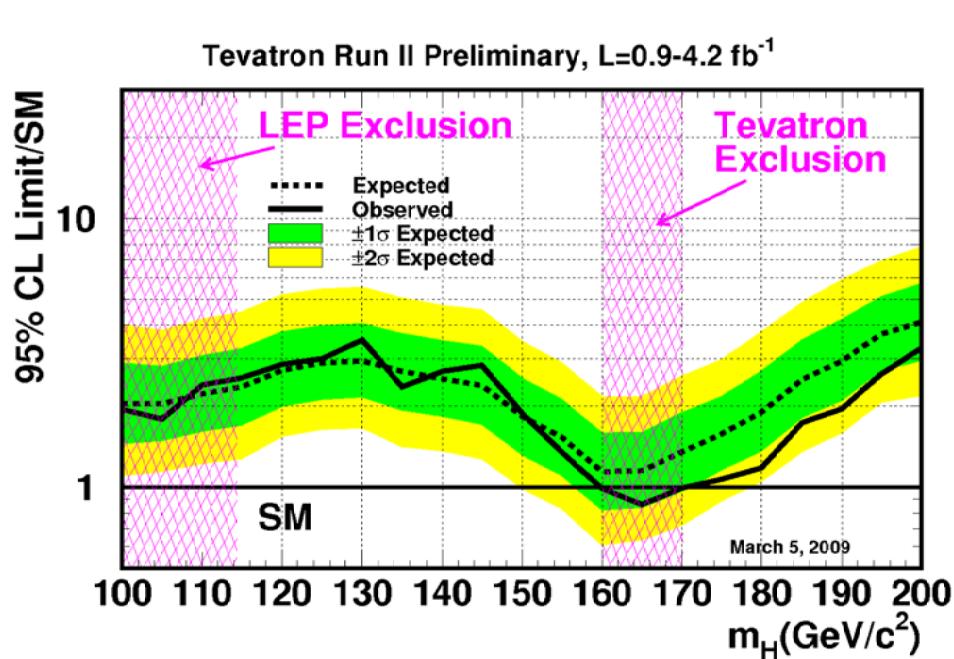
IMPLEMENTATION IN MODELS

- Non-commutative SM Chamseddine, Connes '96,...
Predicted $M_h \approx 170$ GeV



IMPLEMENTATION IN MODELS

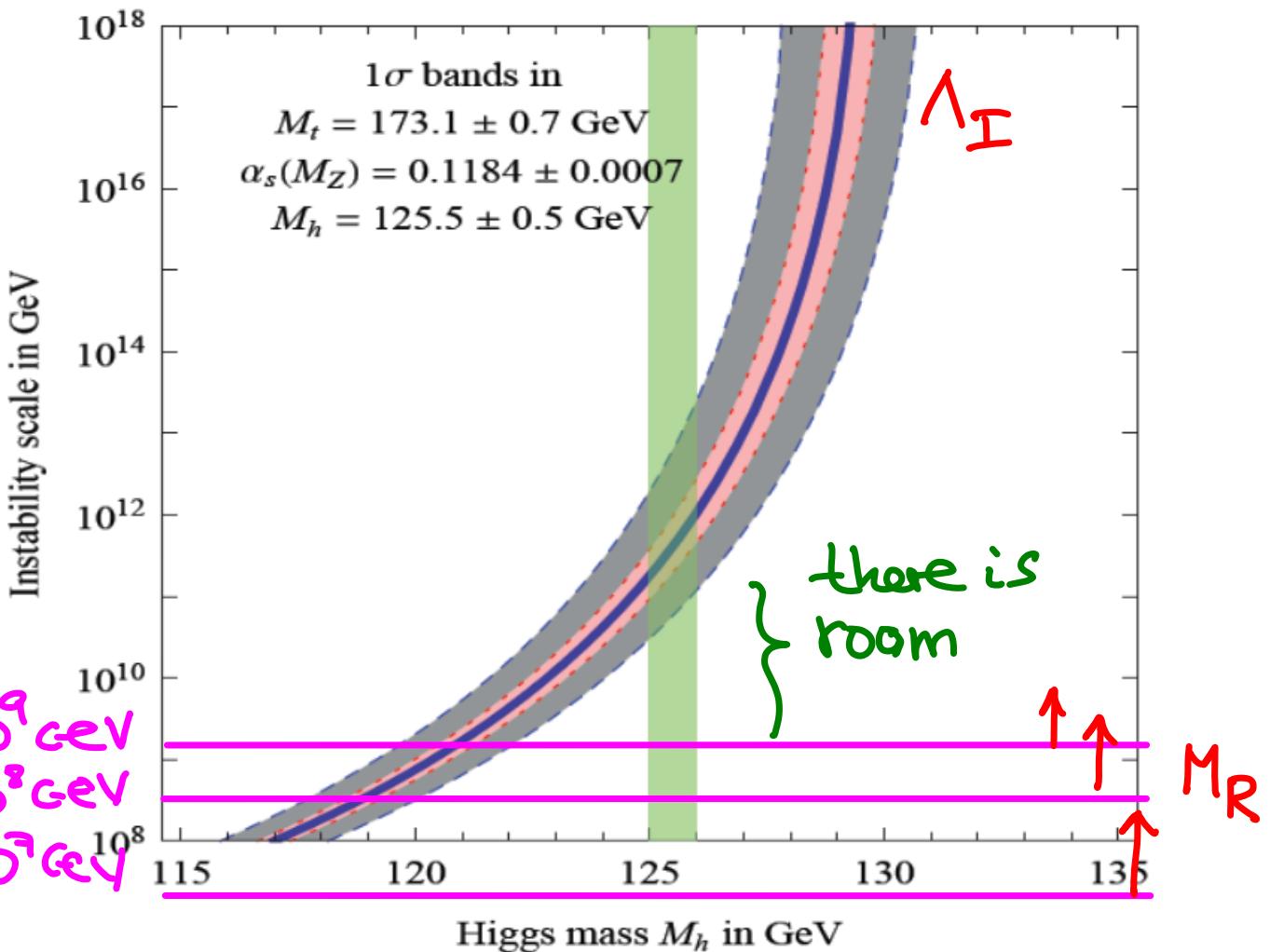
- Non-commutative SM Chamseddine, Connes '12
Predicted $M_h \approx 170$ GeV



Chamseddine, Connes'12
But the model had a singlet and could be resurrected!
Now $M_h \approx 125$ GeV possible...

SEE-SAW IMPLEMENTATION

Use S to generate the ν_R mass: $M_N \sim \langle S \rangle$
Is this compatible with leptogenesis constraints
on M_N ?



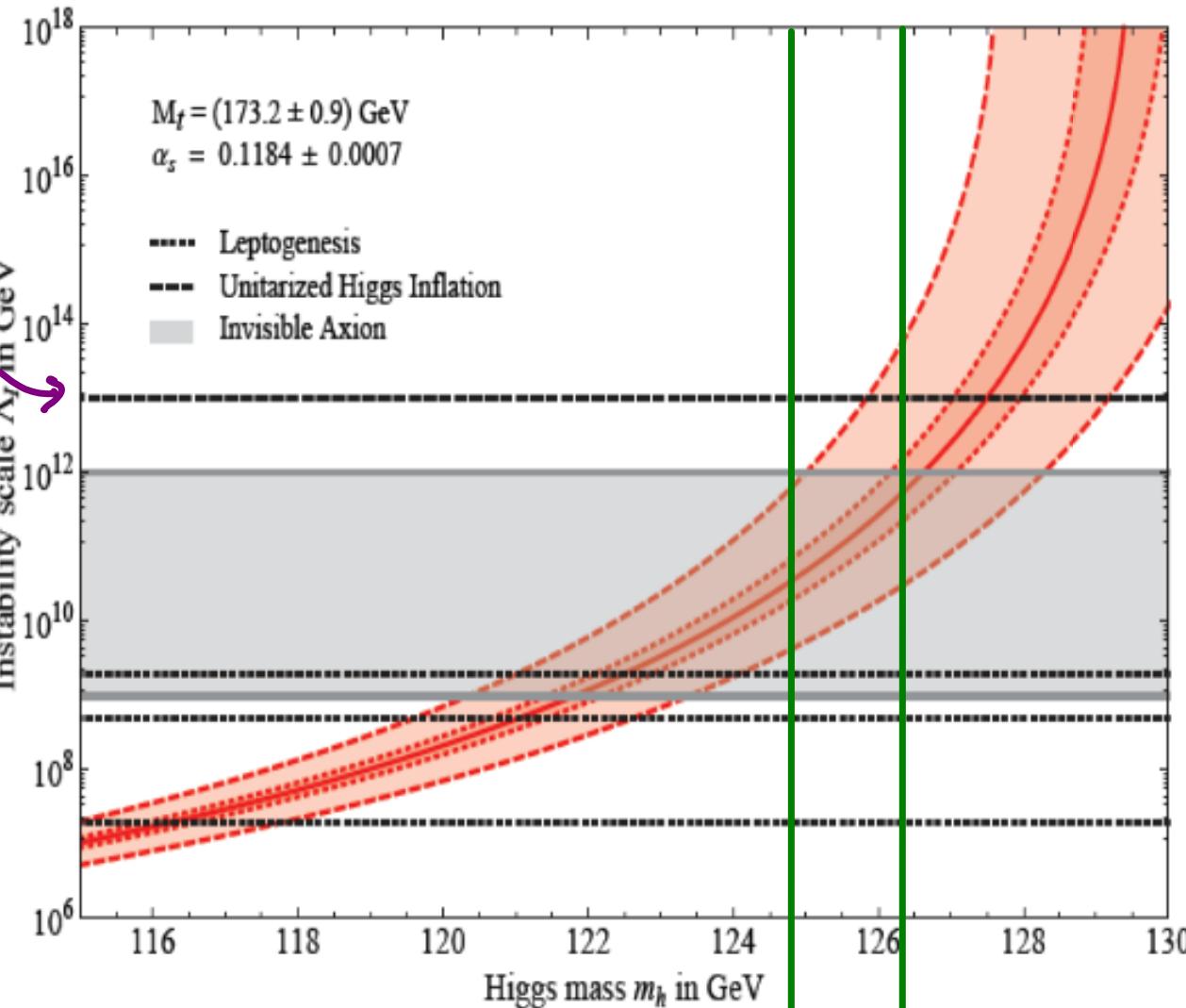
Different
initial
conditions
 ρ_{ν_R} density

$$\left. \begin{array}{l} 2 \times 10^9 \text{ GeV} \\ 5 \times 10^8 \text{ GeV} \\ 2 \times 10^7 \text{ GeV} \end{array} \right\}$$

SINGLET STABILIZATION IN MODELS

Unitarized
Higgs inflation

v_R
+
Leptogenesis



CONCLUSIONS

We finally have data to explore the physics of electroweak symmetry breaking !

- ★ $M_h \simeq 126 \text{ GeV} \Rightarrow$ Unstable EW vacuum w/o BSM
Long-lived and intriguingly close to stability boundary
This instability has implications for cosmology, BSM, ...

★ Singlet stabilization

Robust (tree-level), simple, non-decoupling.

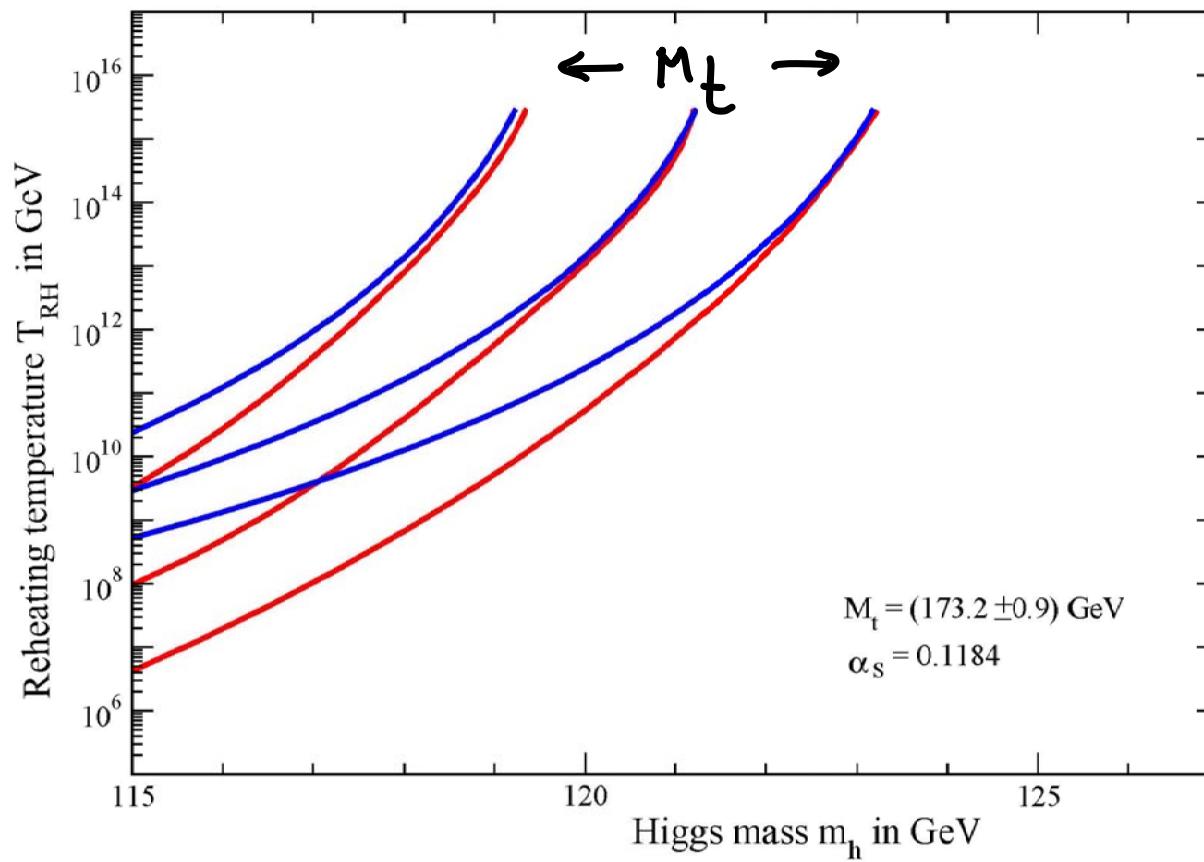
Works in scenarios well motivated for other reasons.

But, let's hope for natural BSM @ LHC 14 !

OTHER IMPLICATIONS

- Cosmology :

Thermal fluctuations can induce vacuum decay



Bound on T_{RH} ?

OTHER IMPLICATIONS

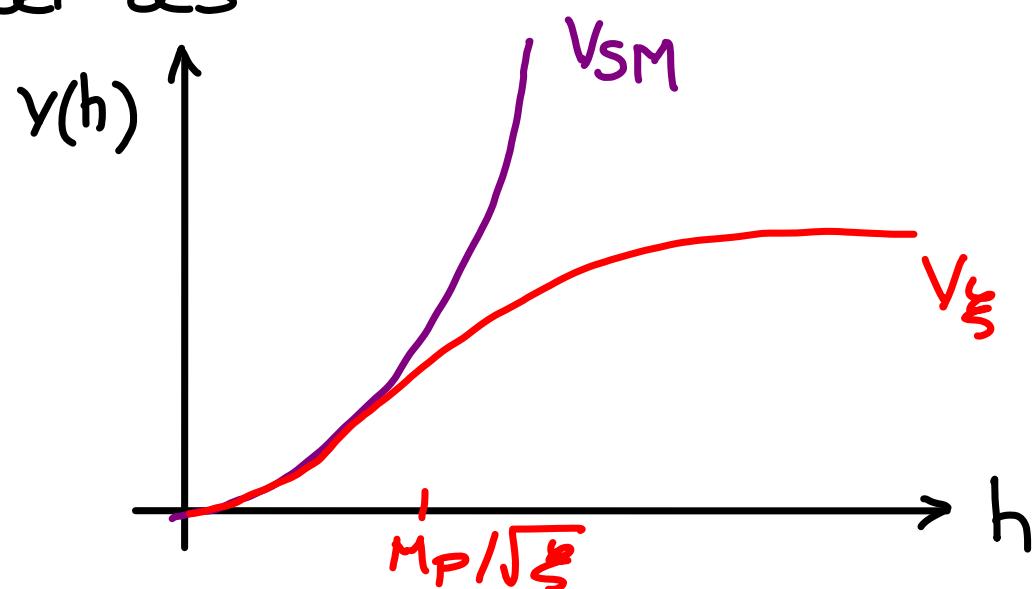
- Cosmology: Higgs inflation Bezrukov, Shaposhnikov '07

Higgs coupled to gravity as $\mathcal{L} \supset \int \sqrt{-g} \xi |H|^2 R$

coupling removed by $g_{\mu\nu} \rightarrow g_{\mu\nu} (1 + \xi h^2/M_P^2)^{-1}$

rescales the potential as

$$v(h) \Rightarrow \frac{v(h)}{(1 + \xi h^2/M_P^2)^2}$$



Requires $\xi \sim 10^4$ to give the right spectrum of primordial fluctuations.

(MORE) TROUBLE FOR HIGGS INFLATION

*1 Effective theory with cutoff

$$\Lambda \sim \frac{M_P}{\xi} \ll \Lambda_{HI} \sim \frac{M_P}{\sqrt{\xi}}$$

Can't trust the plateau region

Burgess, Lee, Trott '09. Barbou, JRE '09

*2 Stability up to $\sim 10\Lambda_{HI}$ is a must.

Requires marginal values of M_h & M_T

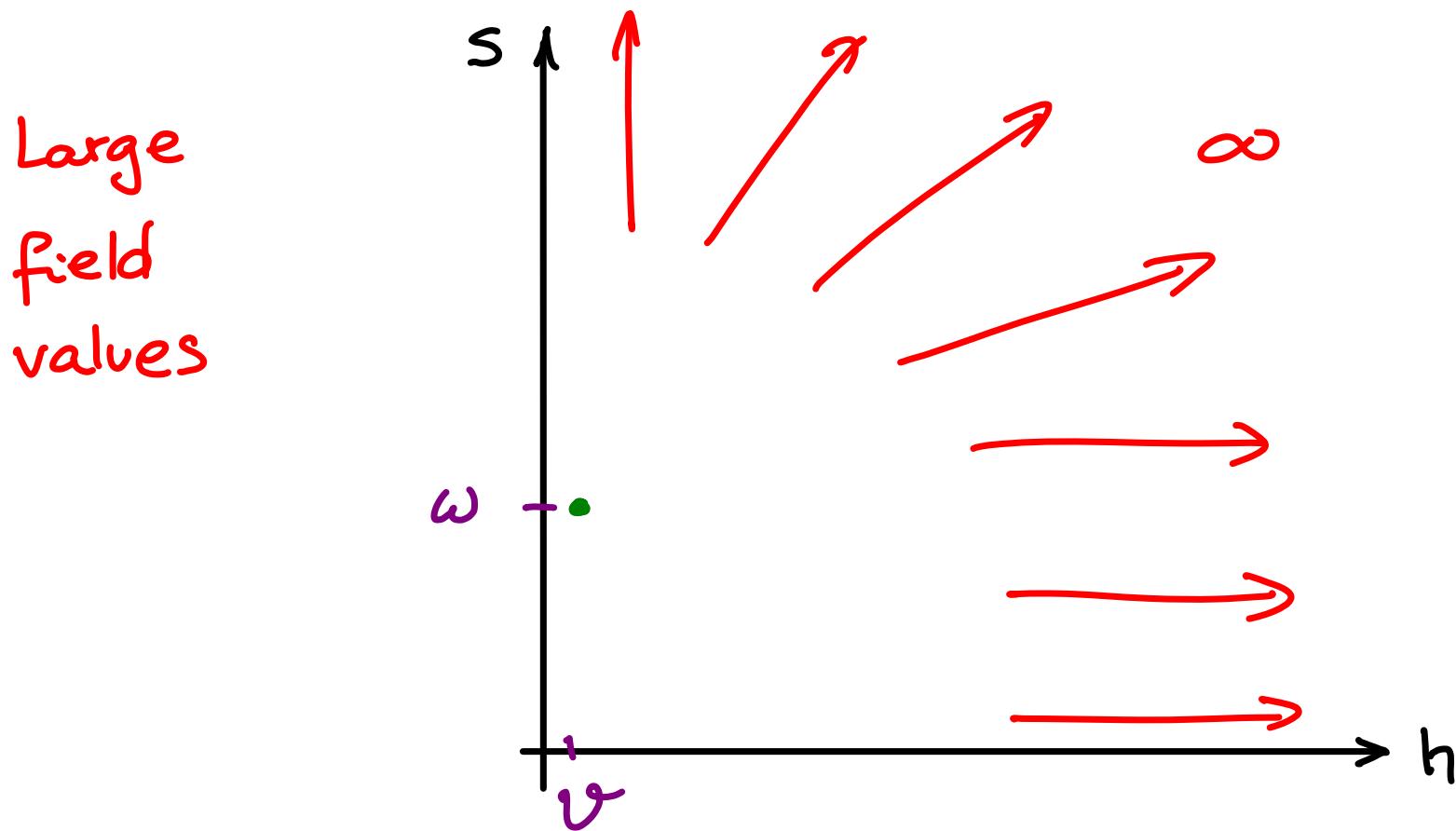
ERROR BUDGET OF STAB. BOUND

Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	± 1.4 GeV
α_s	experimental uncertainty in α_s	± 0.5 GeV
Experiment	Total combined in quadrature	± 1.5 GeV
λ	scale variation in λ	± 0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\text{QCD}})$ correction to M_t	± 0.6 GeV
y_t	QCD threshold at 4 loops	± 0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	± 0.2 GeV
Theory	Total combined in quadrature	± 1.0 GeV

Table 1: Dominant sources of experimental and theoretical errors in the computation of the SM stability bound on the Higgs mass, eq. (2).

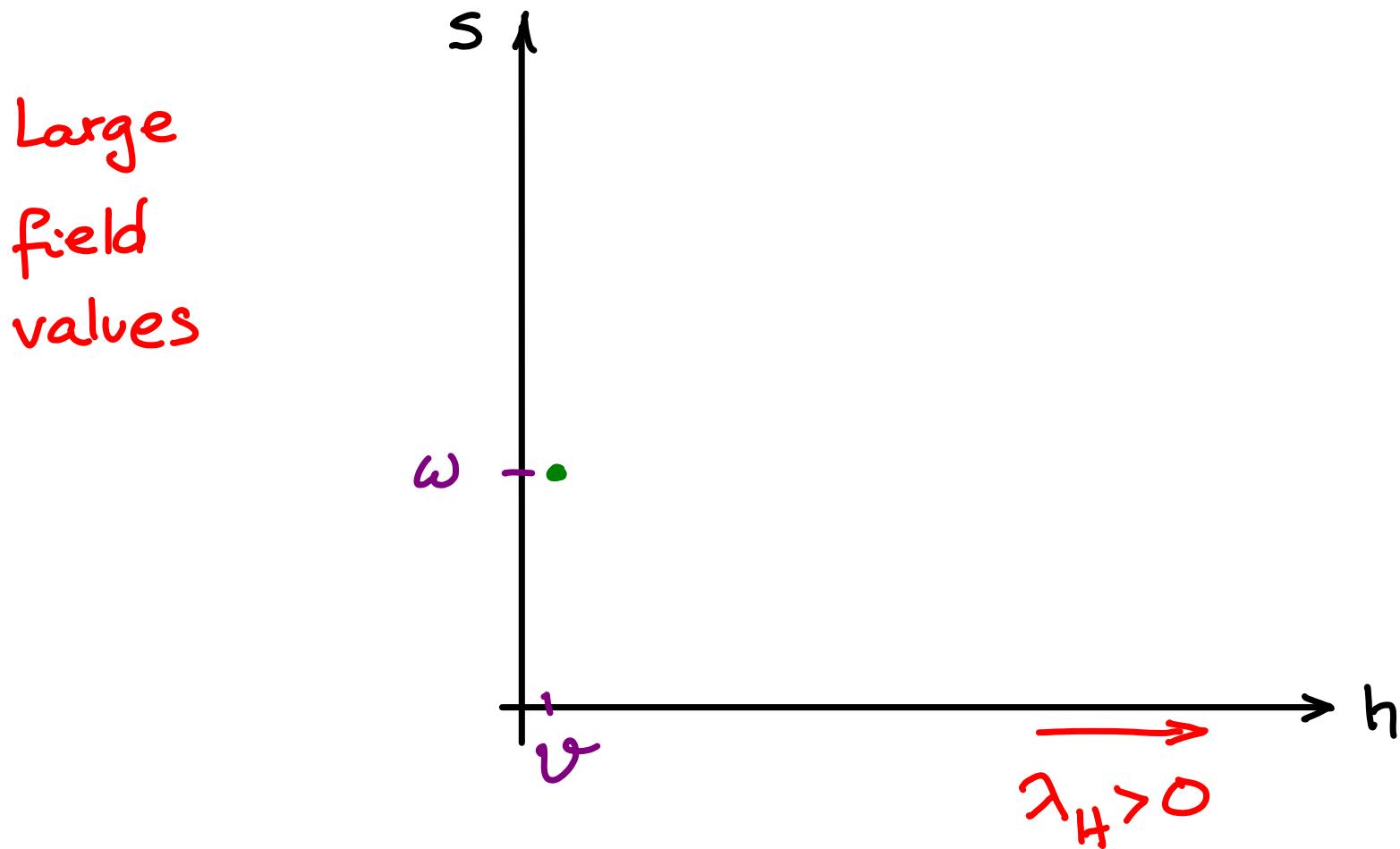
STABILITY CONDITIONS

$$V = \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS} |H|^2 |S|^2$$



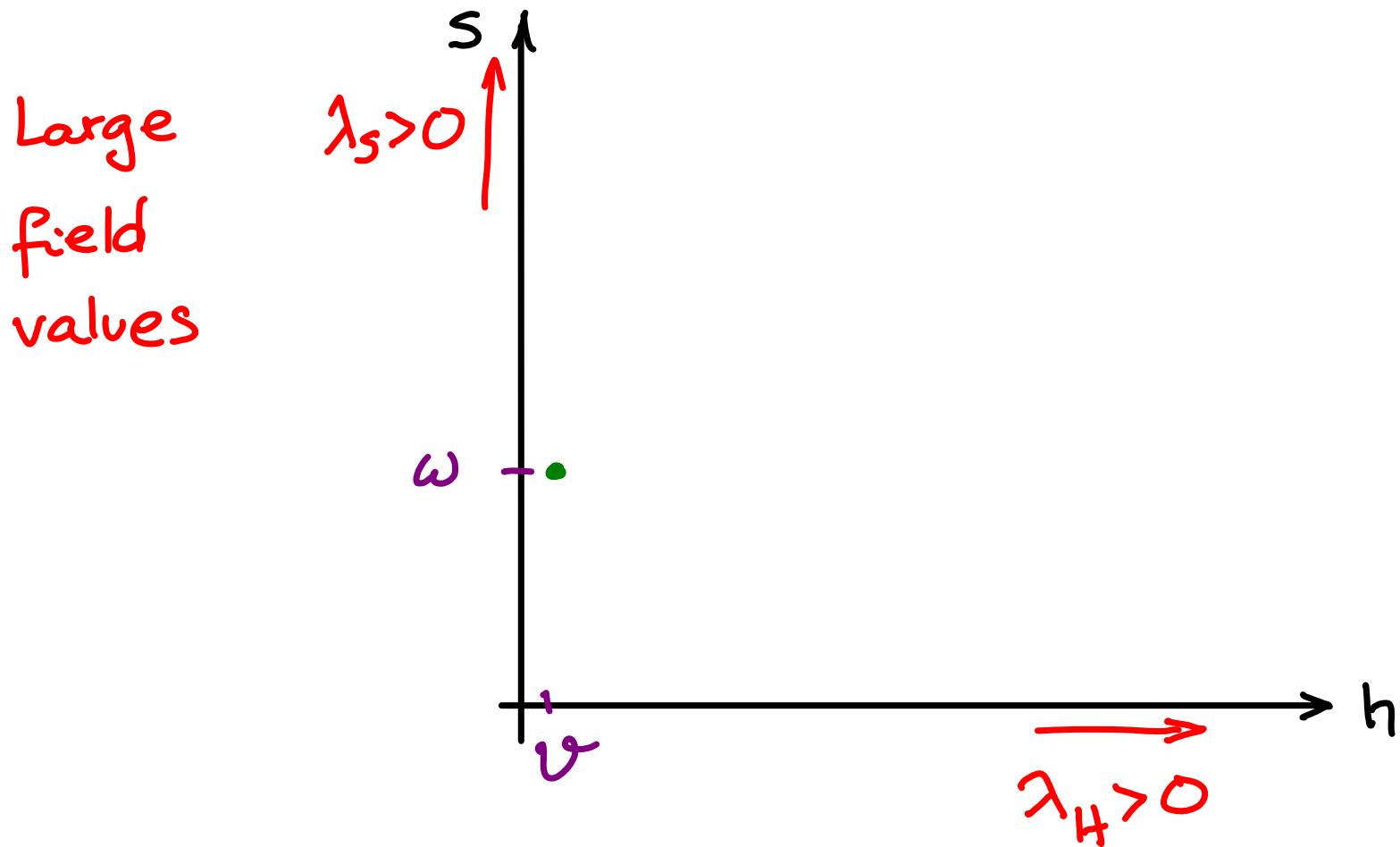
STABILITY CONDITIONS

$$V = \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS} |H|^2 |S|^2$$



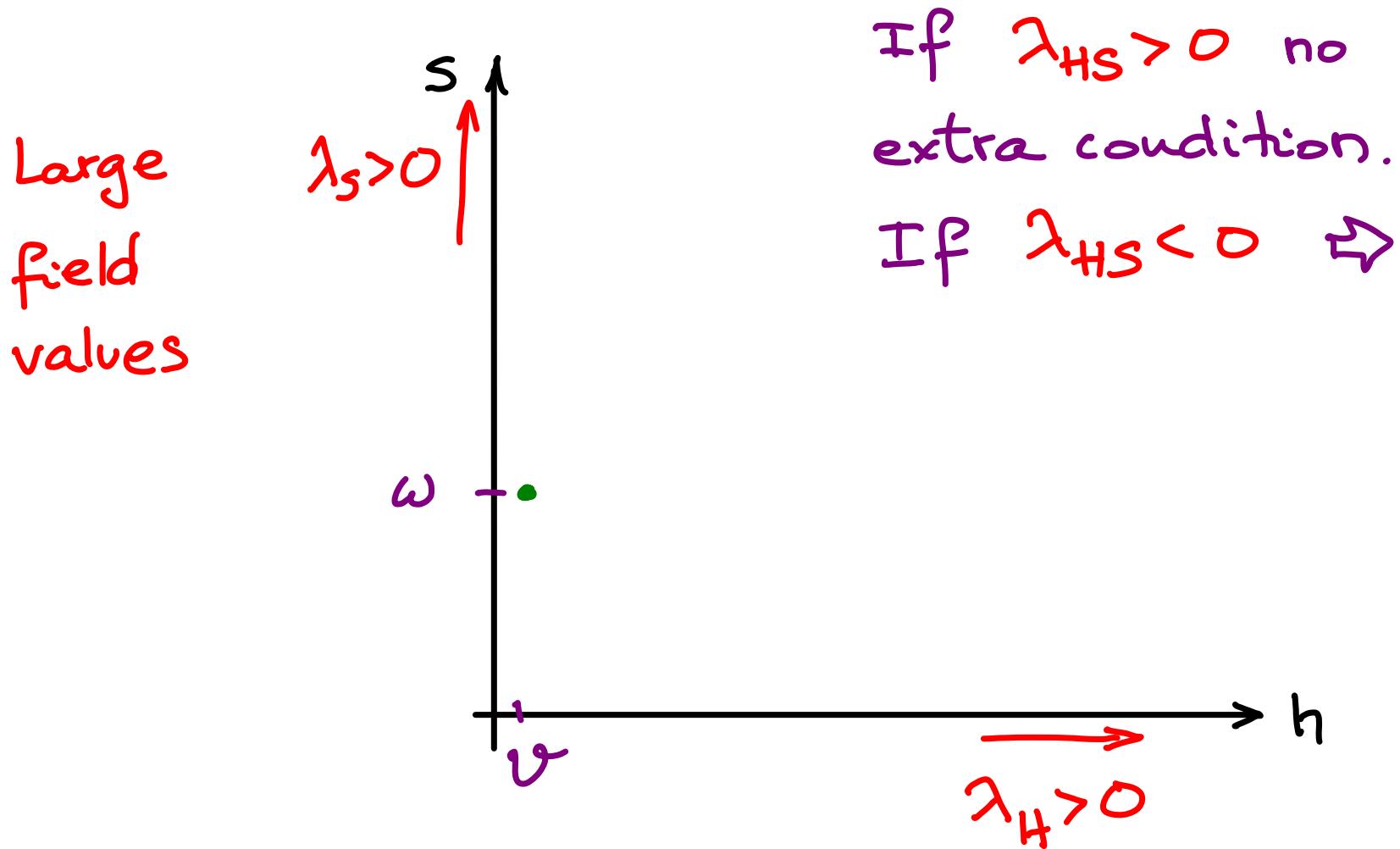
STABILITY CONDITIONS

$$V = \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS} |H|^2 |S|^2$$



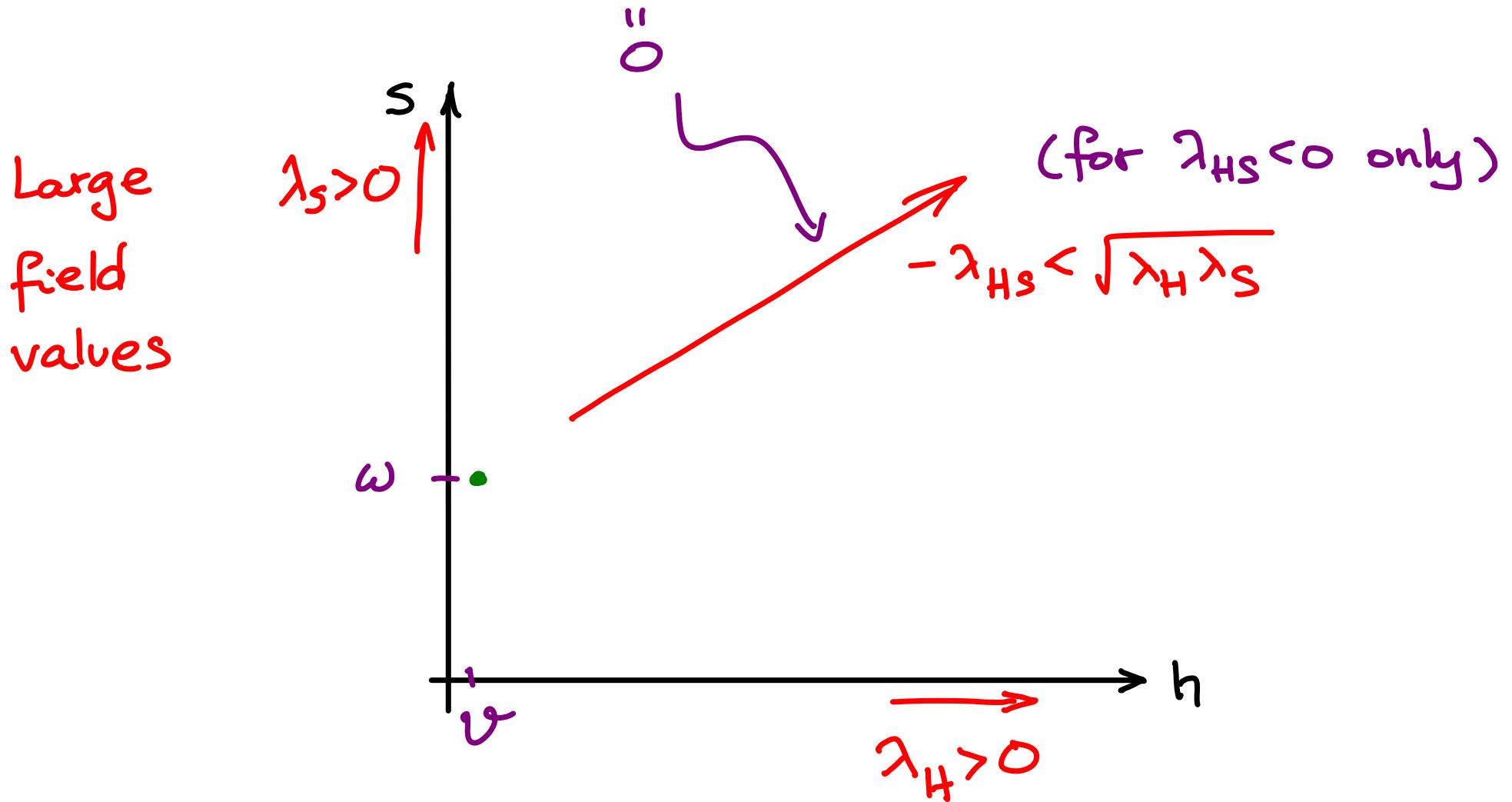
STABILITY CONDITIONS

$$V = \lambda_H |H|^4 + \lambda_S |S|^4 + 2\lambda_{HS} |H|^2 |S|^2$$



STABILITY CONDITIONS

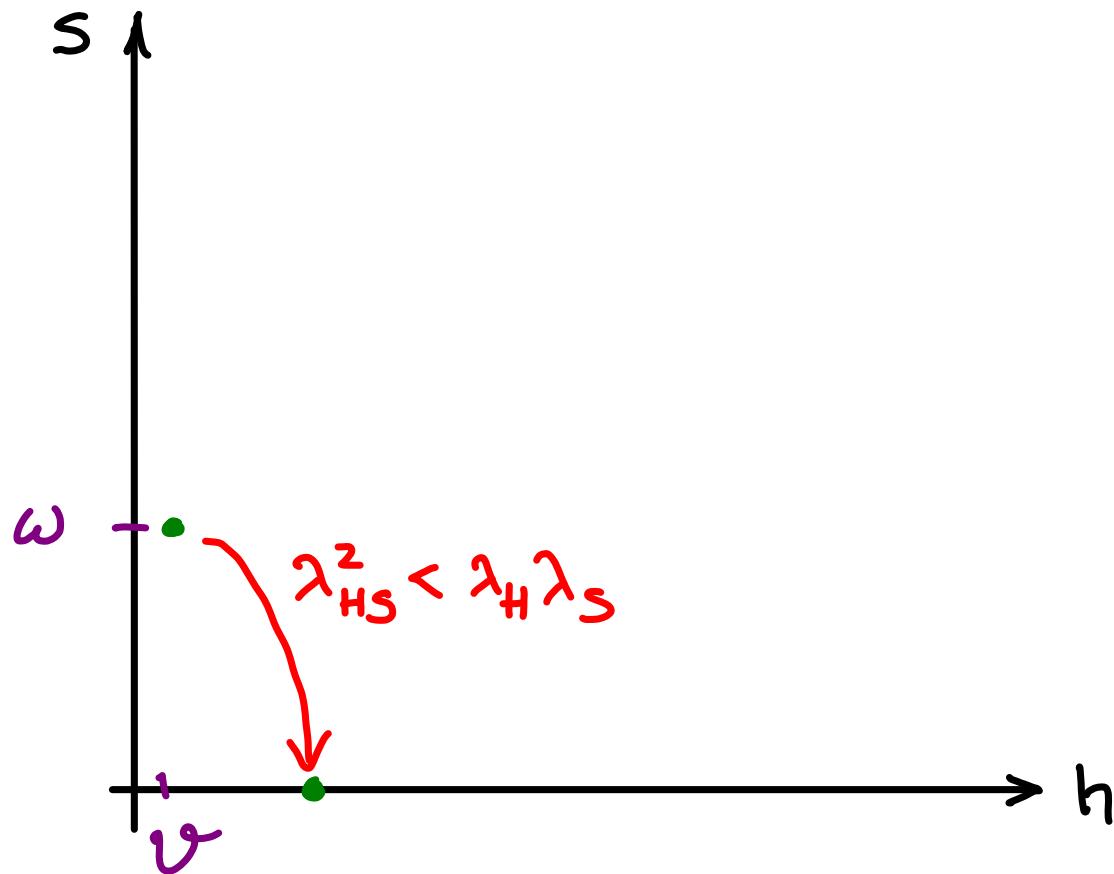
$$V = \frac{1}{4\lambda_H} \left\{ \underbrace{(\lambda_H |H|^2 + \lambda_{HS} |S|^2)^2}_{''O''} + (\lambda_S \lambda_H - \lambda_{HS}^2) |S|^4 \right\}$$



STABILITY CONDITIONS

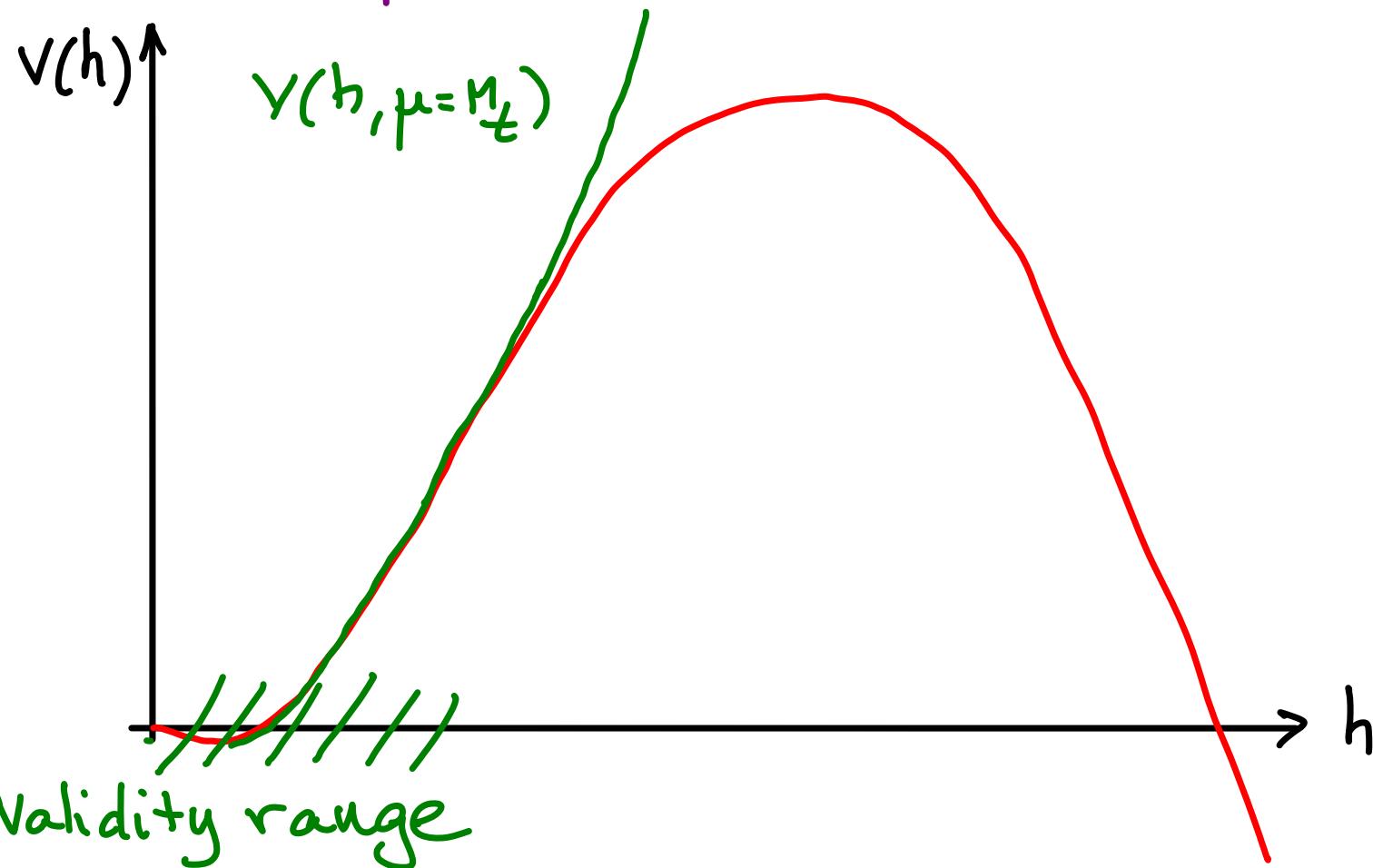
$$V = \lambda_H (|H|^2 - v^2/2)^2 + \lambda_S (S^\dagger S - \omega^2/2)^2 + 2 \lambda_{HS} (|H|^2 - v^2/2)(S^\dagger S - \omega^2/2)$$

Tachyonic
Instability at
Low field
values



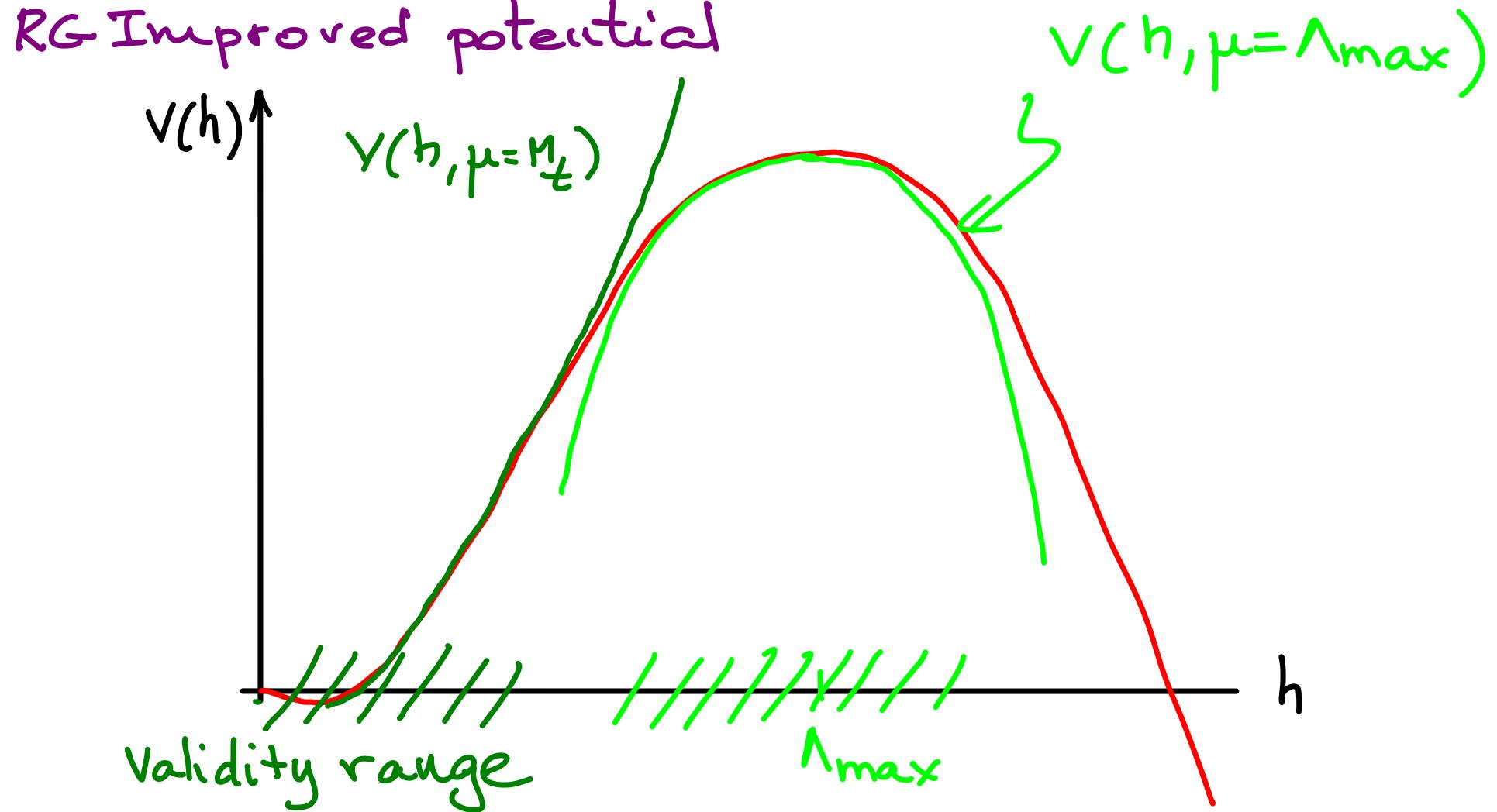
NNLO STABILITY BOUND

RG Improved potential



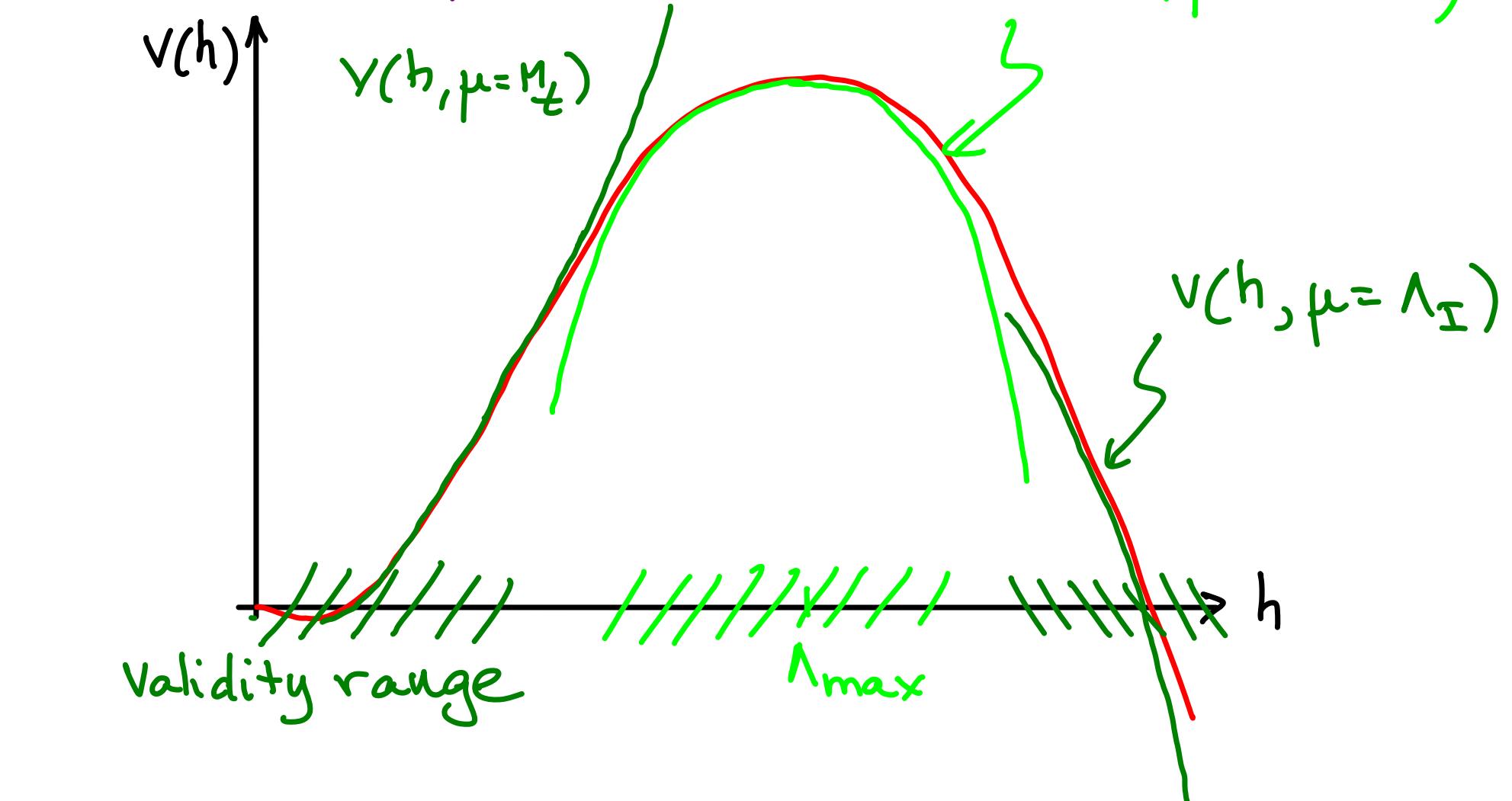
NNLO STABILITY BOUND

RG Improved potential



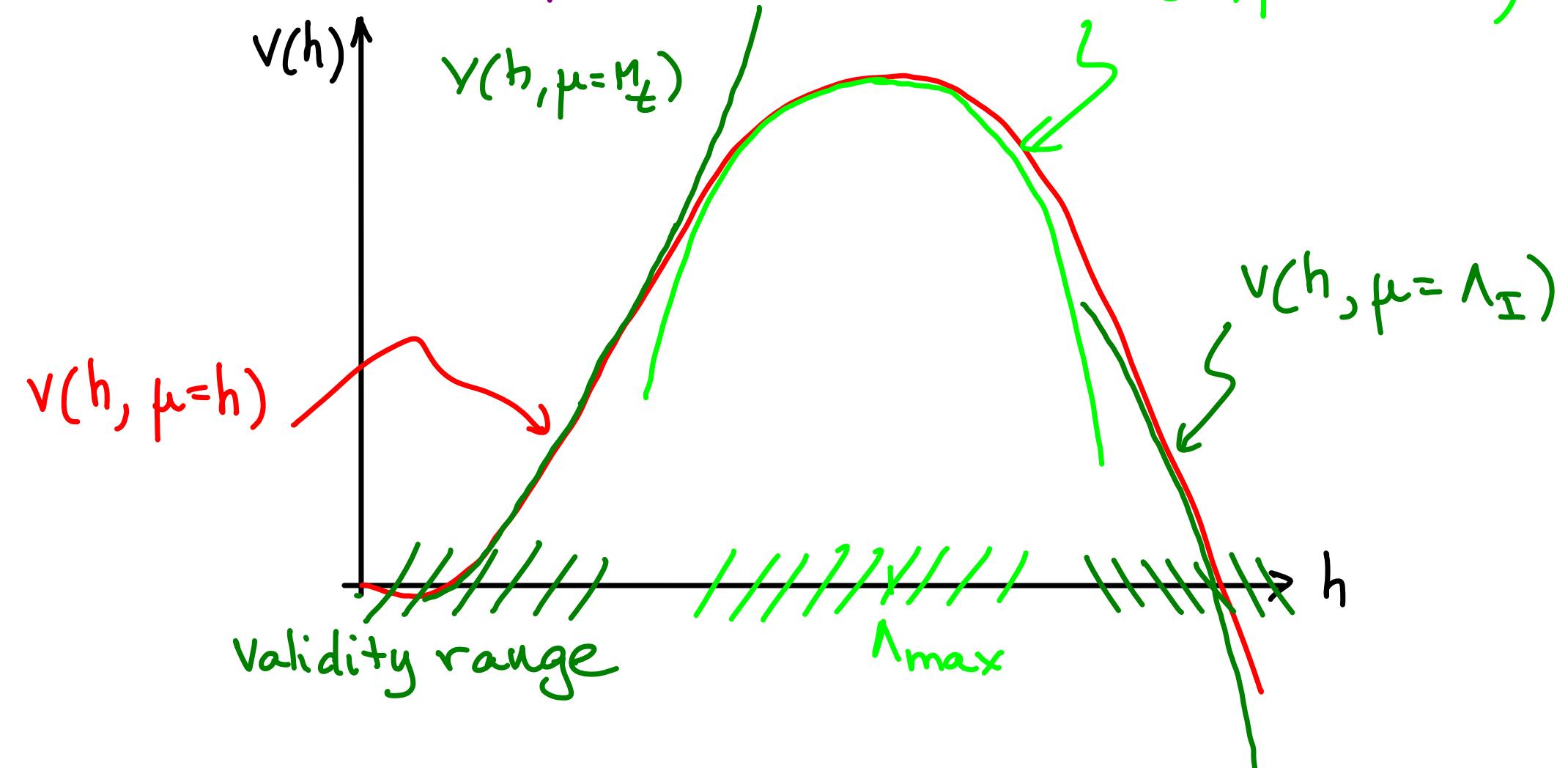
NNLO STABILITY BOUND

RG Improved potential



NNLO STABILITY BOUND

RG Improved potential



Calculation resums $\log(h/M_t)$ up to NNLO order

SM + SINGLET RGES

$$\begin{aligned}(4\pi)^2 \frac{d\lambda_H}{d\ln\mu} &= \left(12y_t^2 - 3g'^2 - 9g^2\right) \lambda_H - 6y_t^4 + \frac{3}{8} \left[2g^4 + (g'^2 + g^2)^2\right] + 24\lambda_H^2 + 4\lambda_{HS}^2, \\ (4\pi)^2 \frac{d\lambda_{HS}}{d\ln\mu} &= \frac{1}{2} \left(12y_t^2 - 3g'^2 - 9g^2\right) \lambda_{HS} + 4\lambda_{HS} (3\lambda_H + 2\lambda_S) + 8\lambda_{HS}^2, \\ (4\pi)^2 \frac{d\lambda_S}{d\ln\mu} &= 8\lambda_{HS}^2 + 20\lambda_S^2.\end{aligned}\tag{2.3}$$