STABILITY OF THE EW VACUUM AFTER LHC

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IFAE

STABILITY OF THE EW VACUUM AFTER LHC

★ Status after first LHC run
HIGGS discovered, no trace of BSM...

★ $M_h \simeq 125$ GeV ⇨ EW Vacuum unstable

★ Several implications of this instability

★ A simple fix (robust and well motivated)

Based on:

J. Elias-Miró, JRE, G.F. Giudice, G. Isidori, A. Riotto, A. Strumia
[hep-ph/1112.3022],
J. Elias-Miró, JRE, G.F. Giudice, H.M. Lee, A. Strumia
[hep-ph/1203.0237]
G. Degrassi, S. Di Vita, J. Elias-Miró, JRE, 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]
O. Lebedev, [hep-ph/1203.0156]

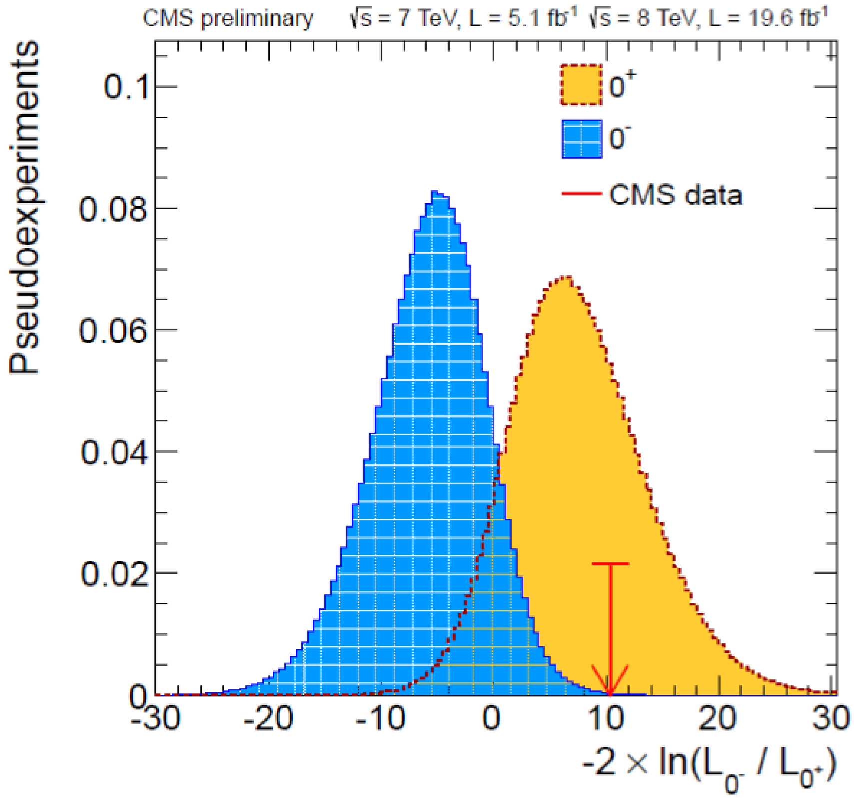
HIGGS BOSON

h^0

HIGGS BOSON

h^0

$J^P = 0^+$



0^- excluded @ 97% CL

HIGGS BOSON

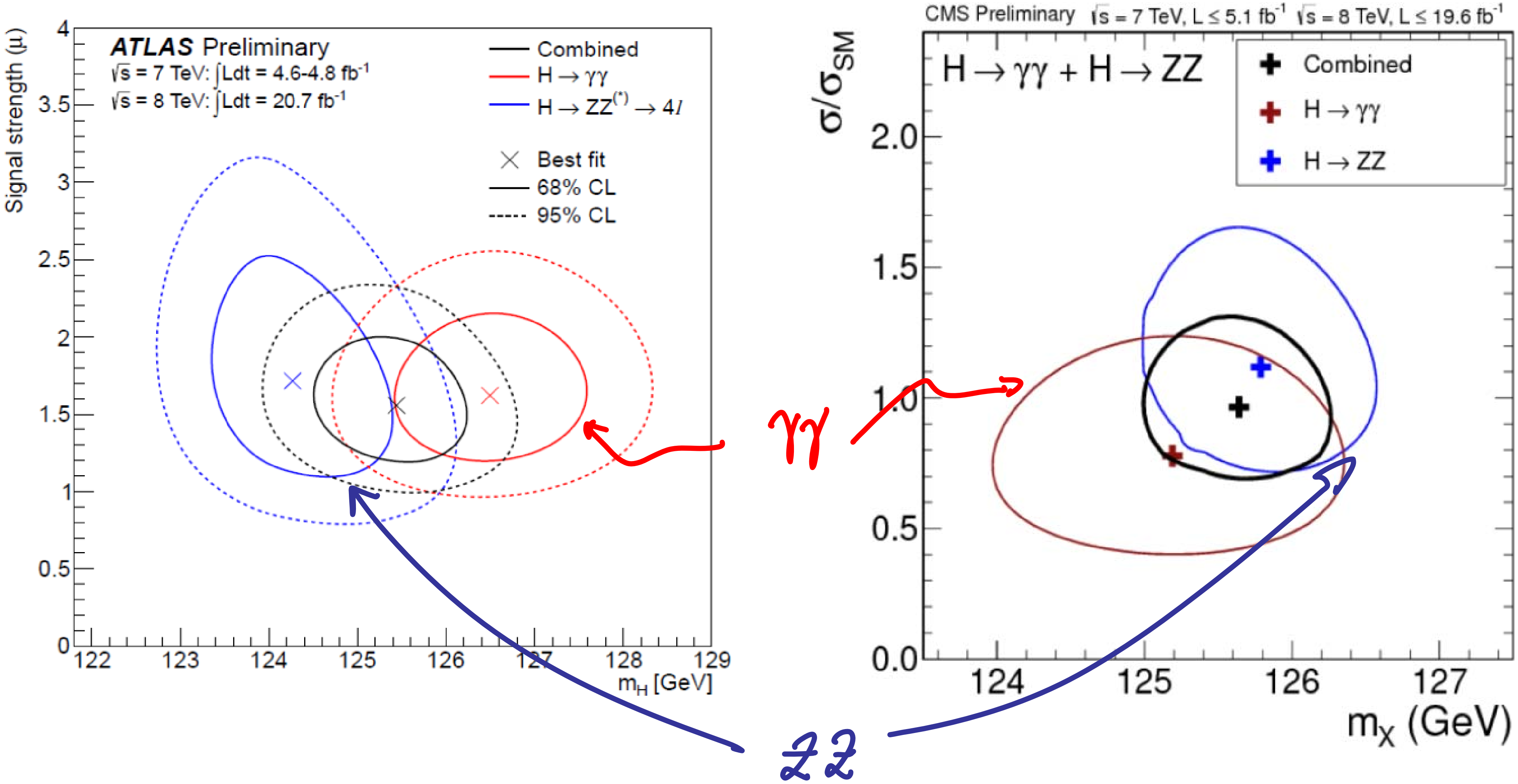
h^0

$J^P = 0^+$

h^0 MASS

VALUE (GeV)	*DOCUMENT ID*
125.5 + 0.2 (stat) + 0.5/-0.6 (syst)	ATLAS-CONF-2013-14
125.7 + 0.3 (stat) + 0.3 (syst)	CMS-PAS-HIG-13-005

MASS DETERMINATION



γγ

ZZ

HIGGS BOSON

h^0

$J^P = 0^+$

---

h^0 MASS

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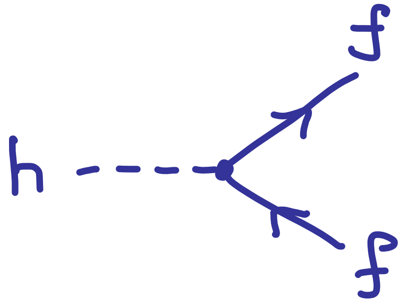
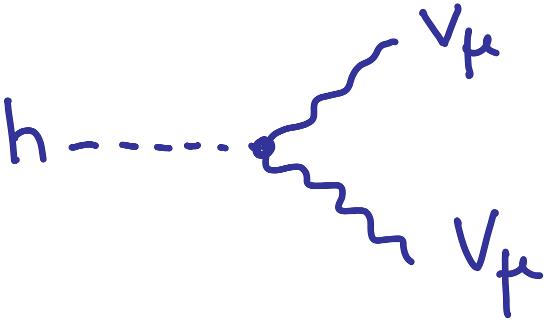
h^0 couplings

HIGGS COUPLINGS SEEN SO FAR

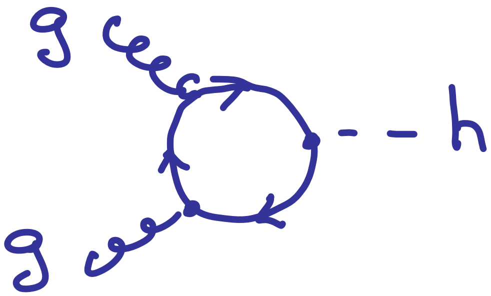


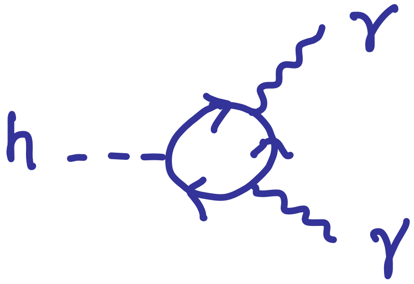
$$f = \left\{ \begin{array}{l} \text{top (indirectly)} \\ \text{bottom} \\ \text{tau} \end{array} \right.$$

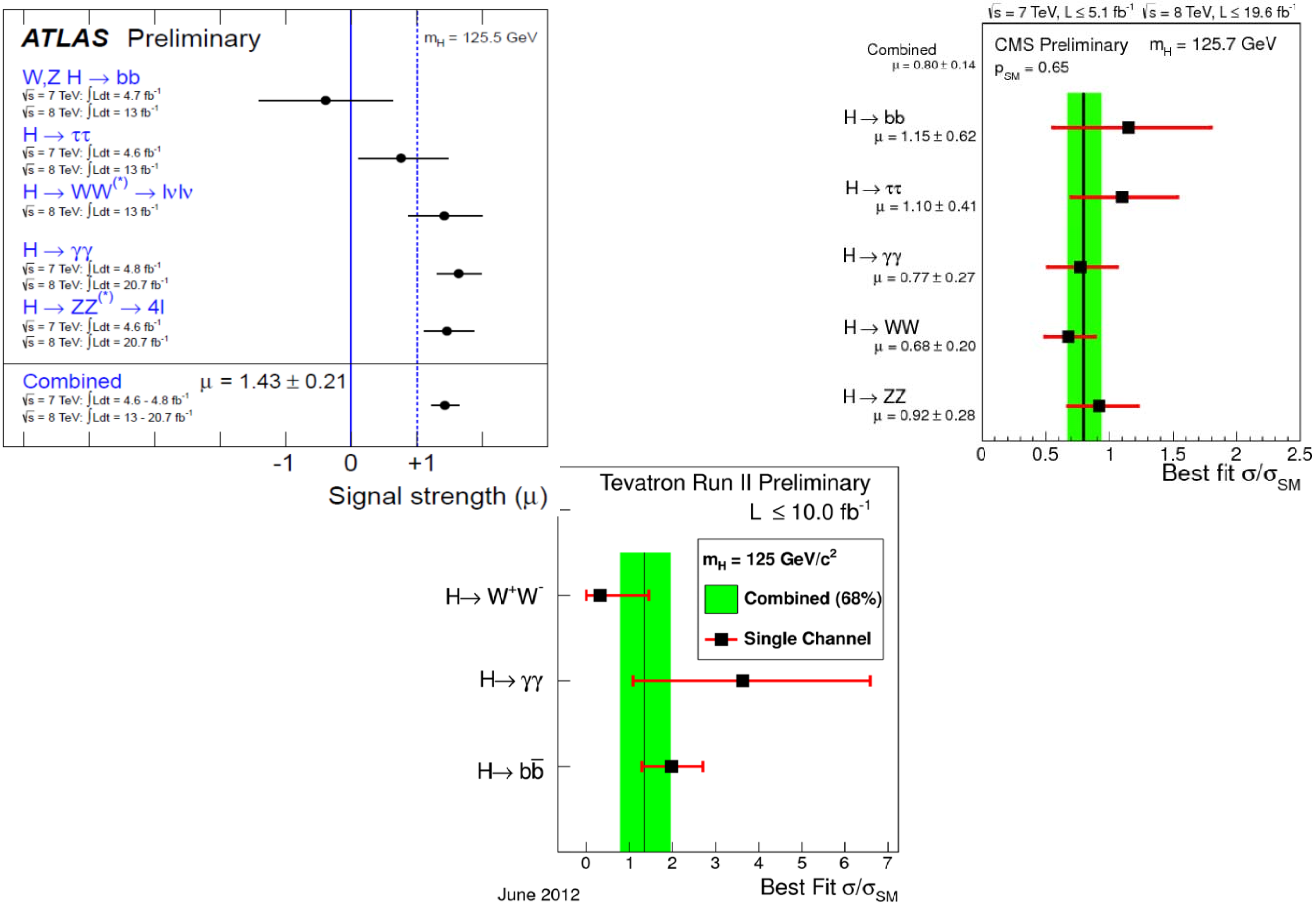


$$V_\mu = \left\{ \begin{array}{l} W \\ Z \end{array} \right.$$

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 0 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

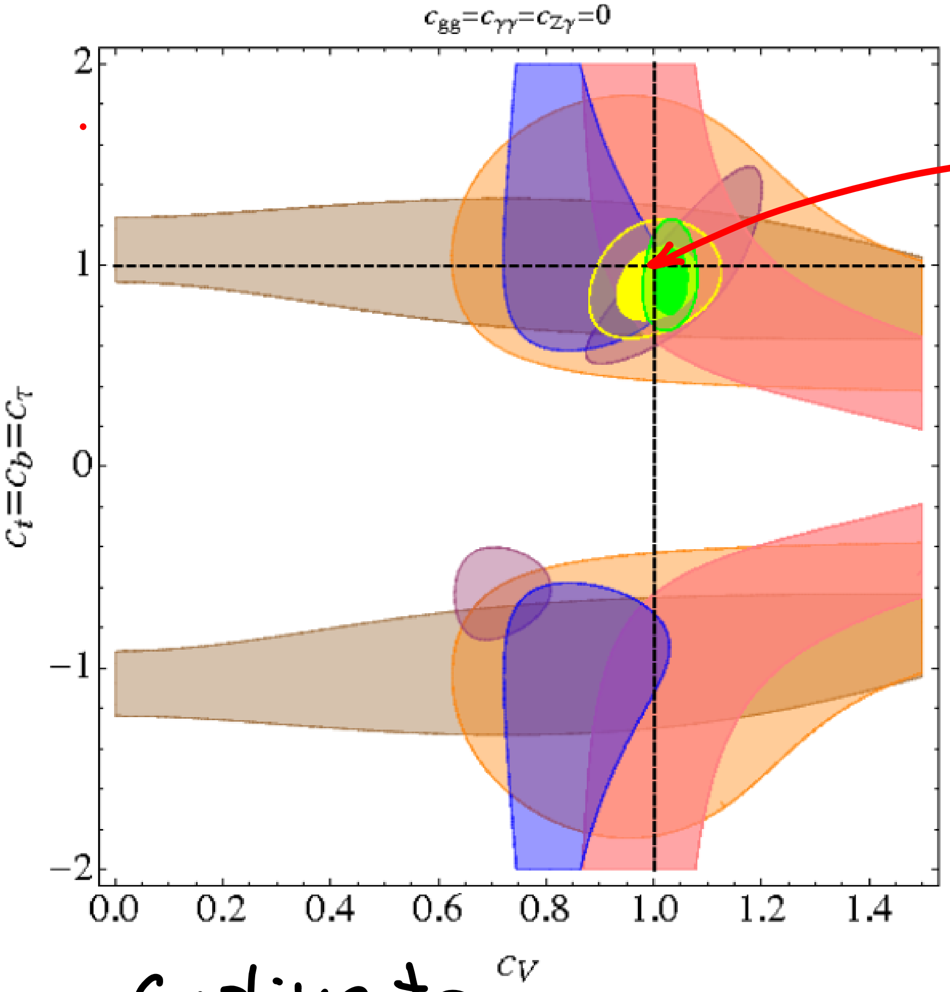
Affected by hierarchy problem

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



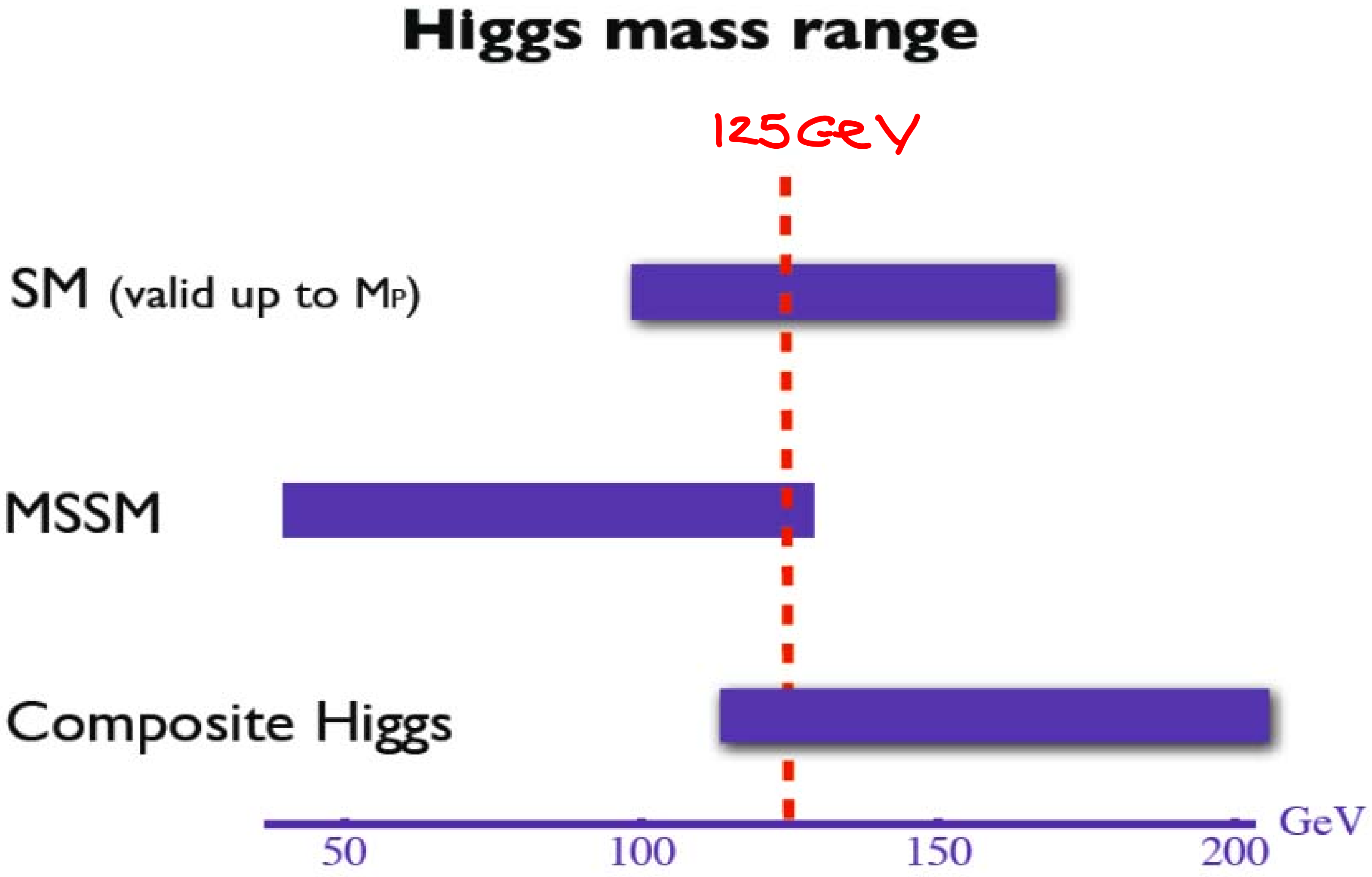
SM

Coupling to fermions

Coupling to gauge bosons

Falkowski, Riva, Urbano'13

M_h AS MODEL DISCRIMINATOR



A. Pomarol, ICHEP'12

WARNING !

YOU ARE LEAVING THE
NATURAL SECTOR

ВЫ ВЫЕЗЖАЕТЕ ИЗ
ПРИРОДНОГО СЕКТОРА

VOUS SORTEZ DU
SECTEUR NATUREL

SIE VERLASSEN DEN NATÜRLICHEN SEKTOR

$M_H \sim 125$ GeV. IMPLICATIONS FOR STABILITY

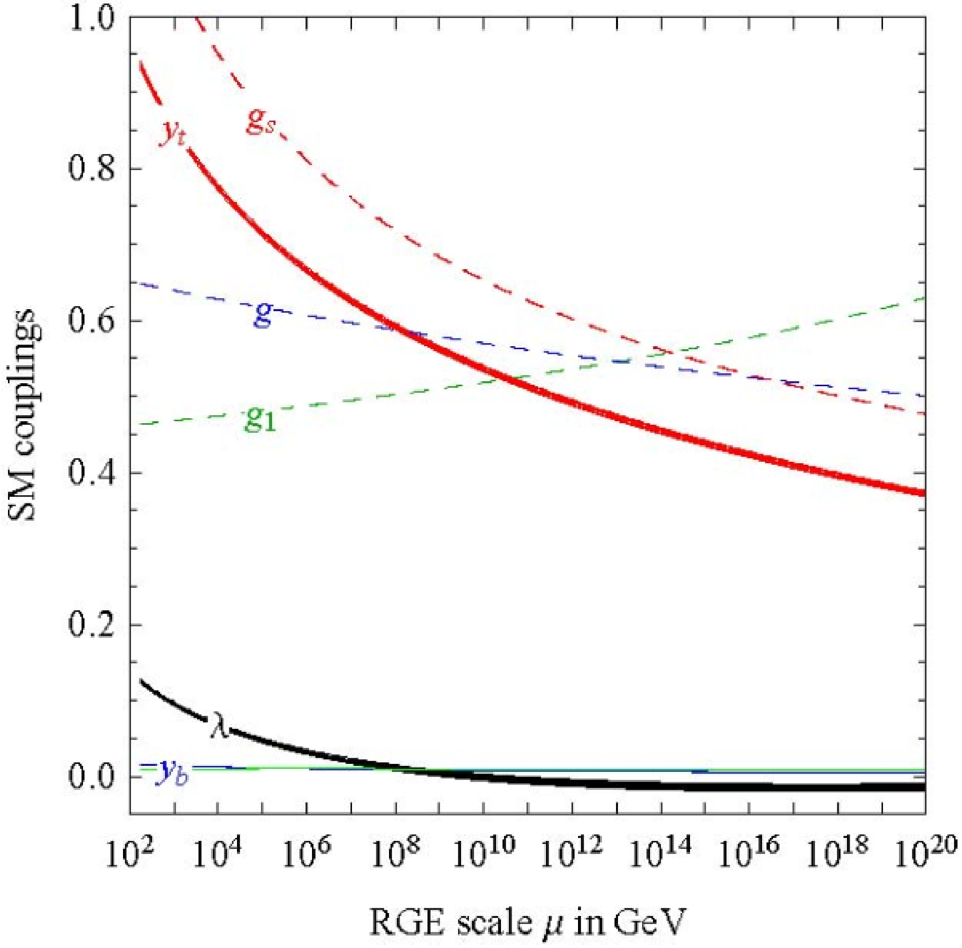
Assume Higgs has SM props. and no BSM Physics

All SM parameters known

$$M_h \Rightarrow \lambda(EW)$$

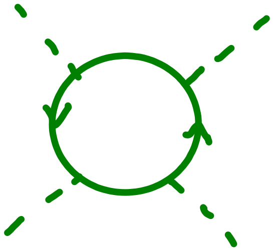
Forgetting naturalness, can the pure SM be valid up to M_{Pl}?

Weakly coupled up to M_{Pl}



VACUUM INSTABILITY

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

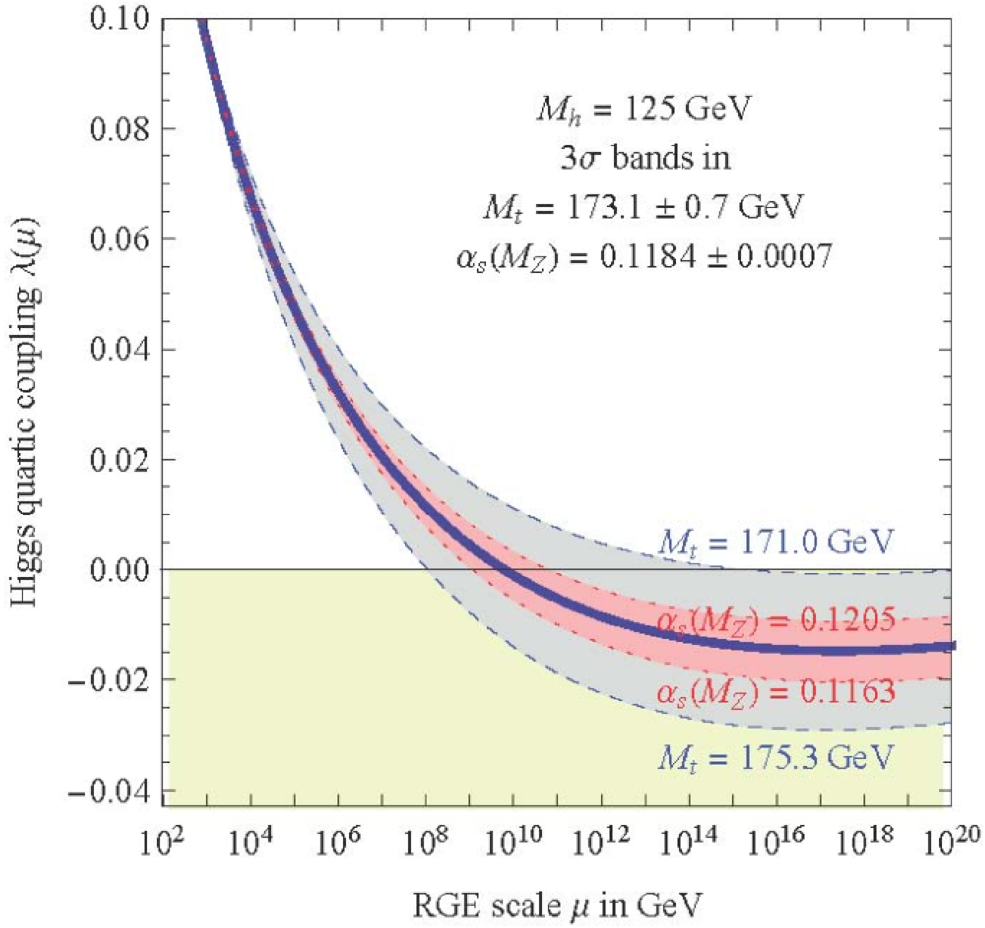


$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

⇓

Higgs potential instability

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



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

VACUUM INSTABILITY

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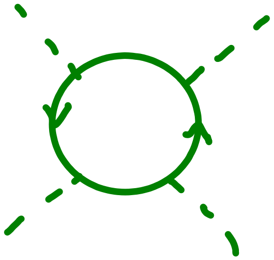

$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

$$\Downarrow$$

Higgs potential instability

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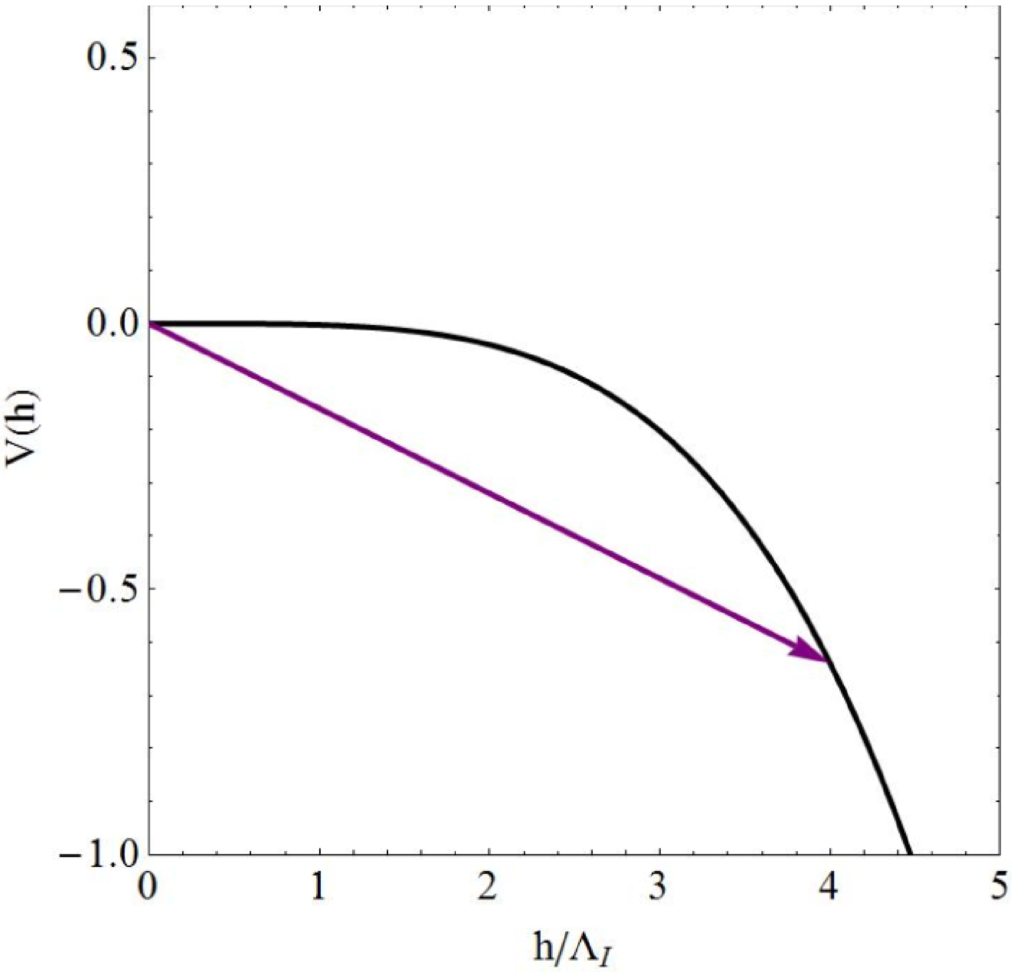


LIFE IN A METASTABLE VACUUM

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

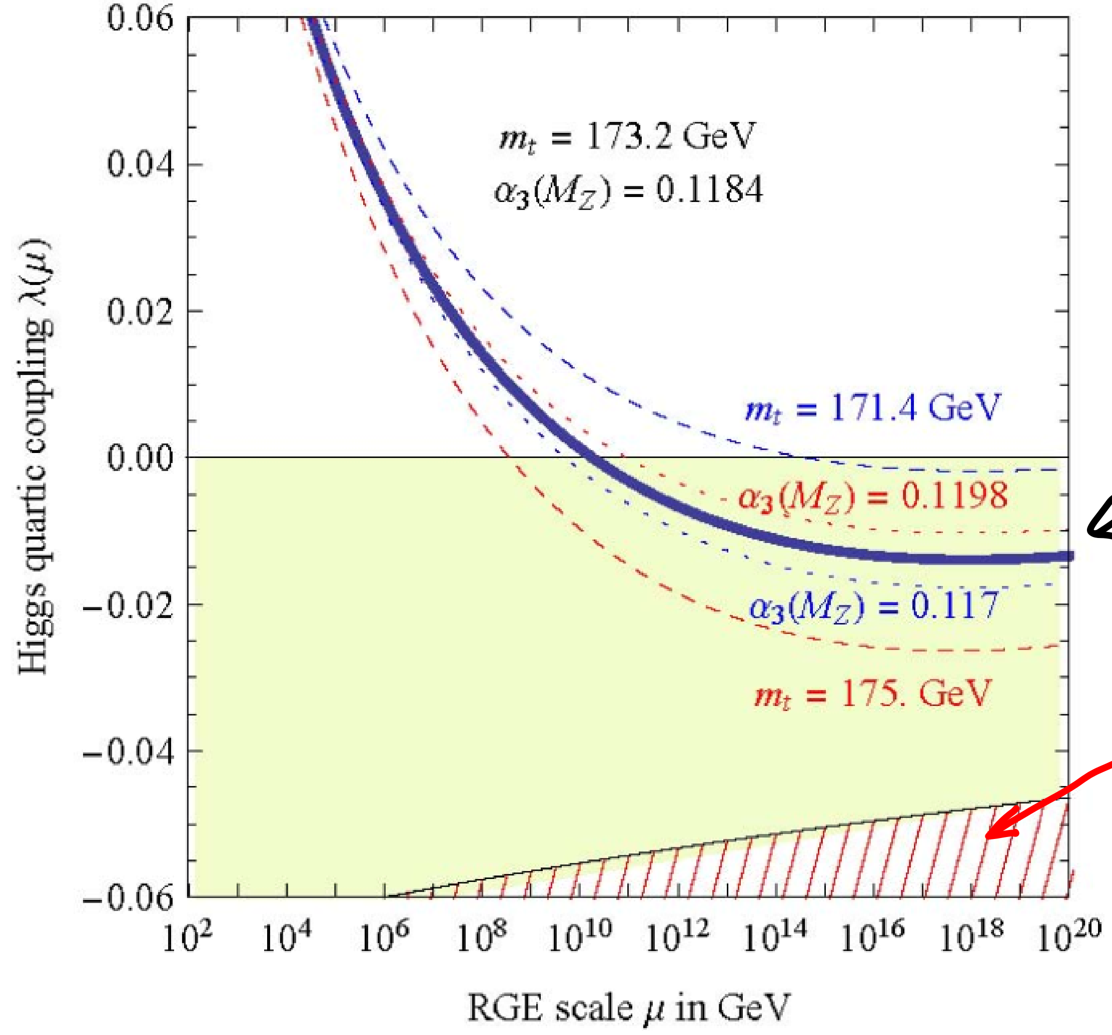
$$h^4 e^{-S_4} \sim h^4 \exp\left(-\frac{8\pi^2}{3|\lambda(h)|}\right) \sim h^4 \exp\left[-\frac{2600}{|\lambda|/0.01}\right]$$

easily wins over τ_U^4

$p \lll 1$: Lifetime of EW vacuum much longer than τ_U

LIFE IN A METASTABLE VACUUM

$m_h = 126$ GeV



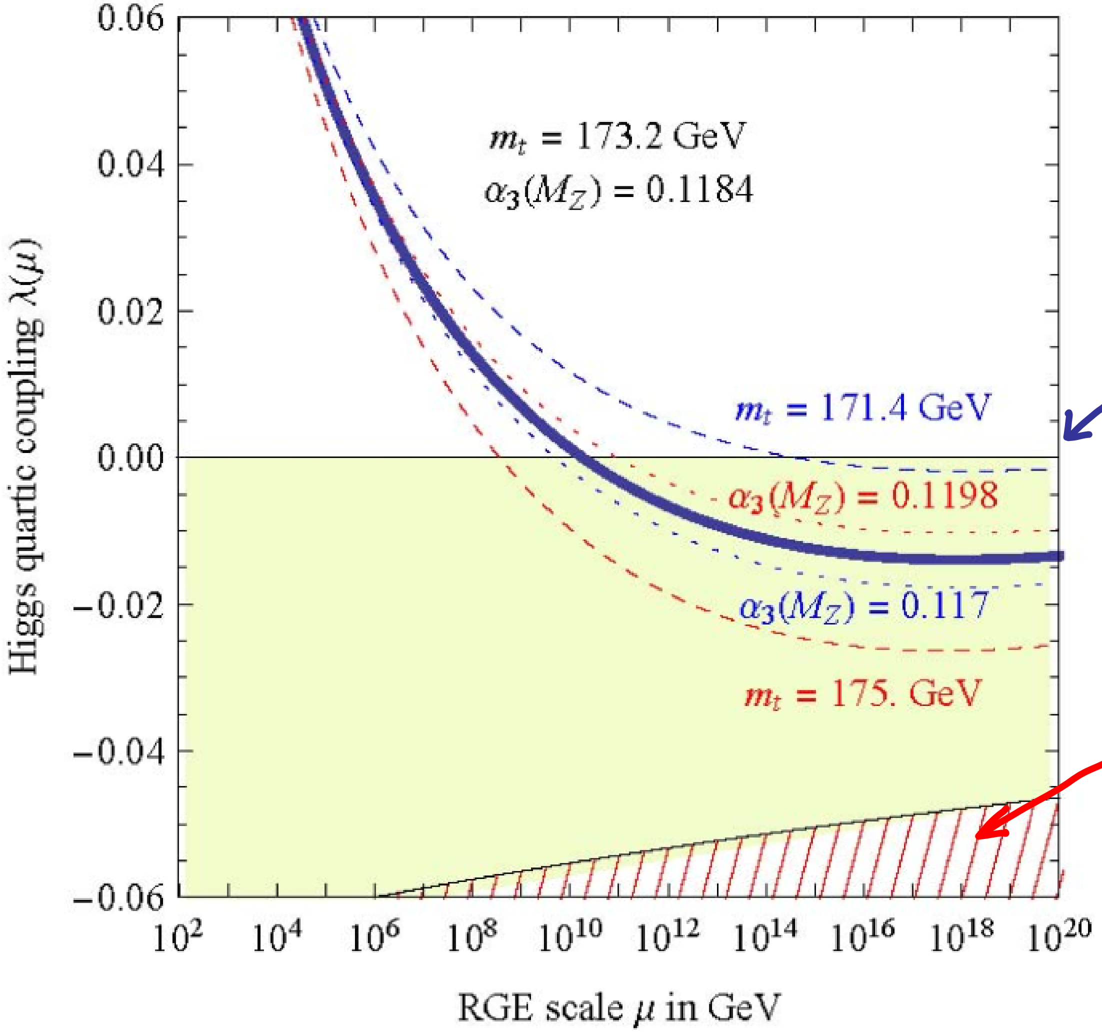
Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

$p > 1$
Unstable
Vacuum

LIFE IN A METASTABLE VACUUM

$m_h = 126$ GeV



Stability Still Possible ?

$p > 1$
Unstable
Vacuum

NNLO STABILITY BOUND

For stability up to M_{Pl} :

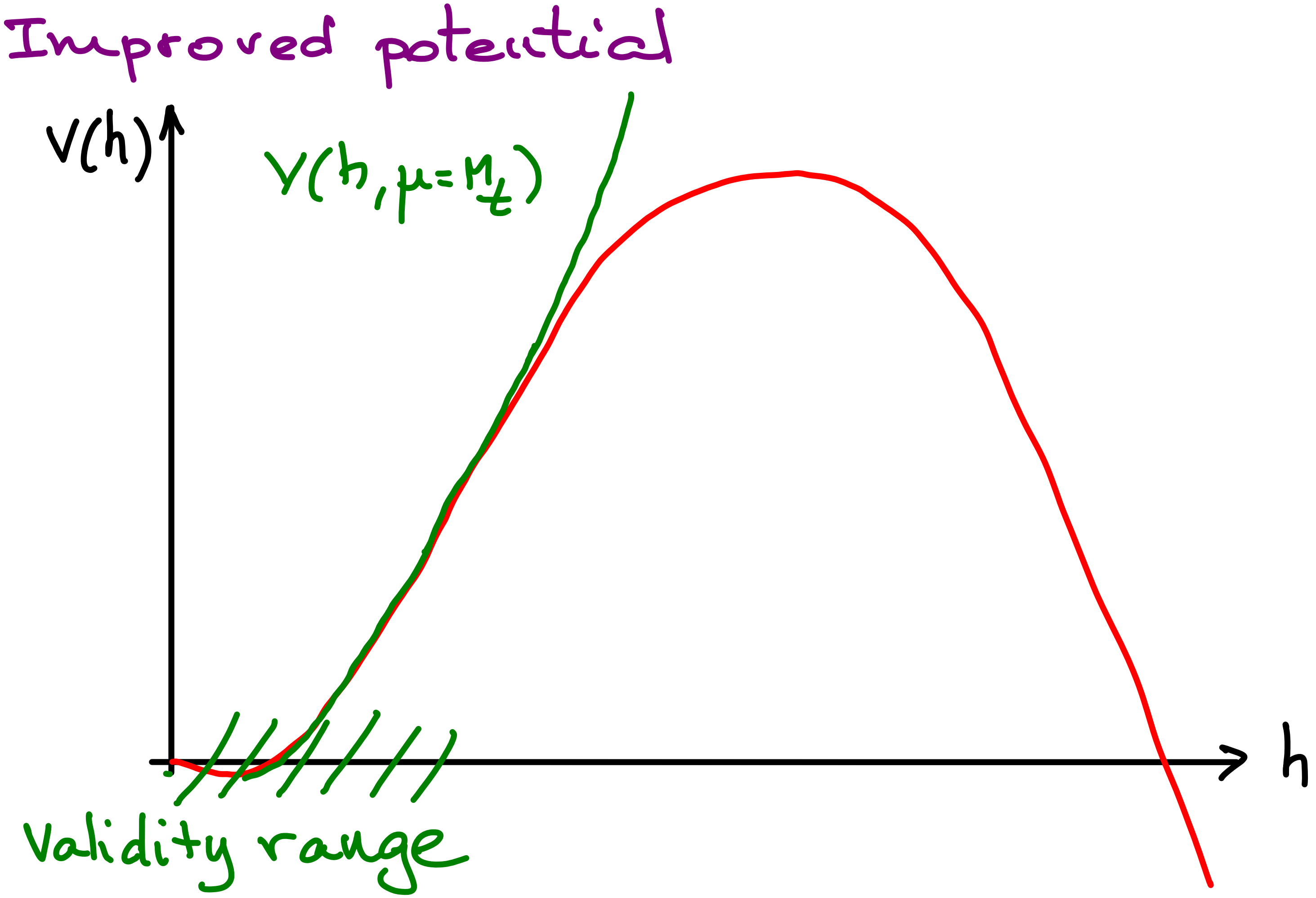
$$M_h\,[\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t(\mathrm{GeV}) - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{th}$$

State-of-the-art NNLO calculation:

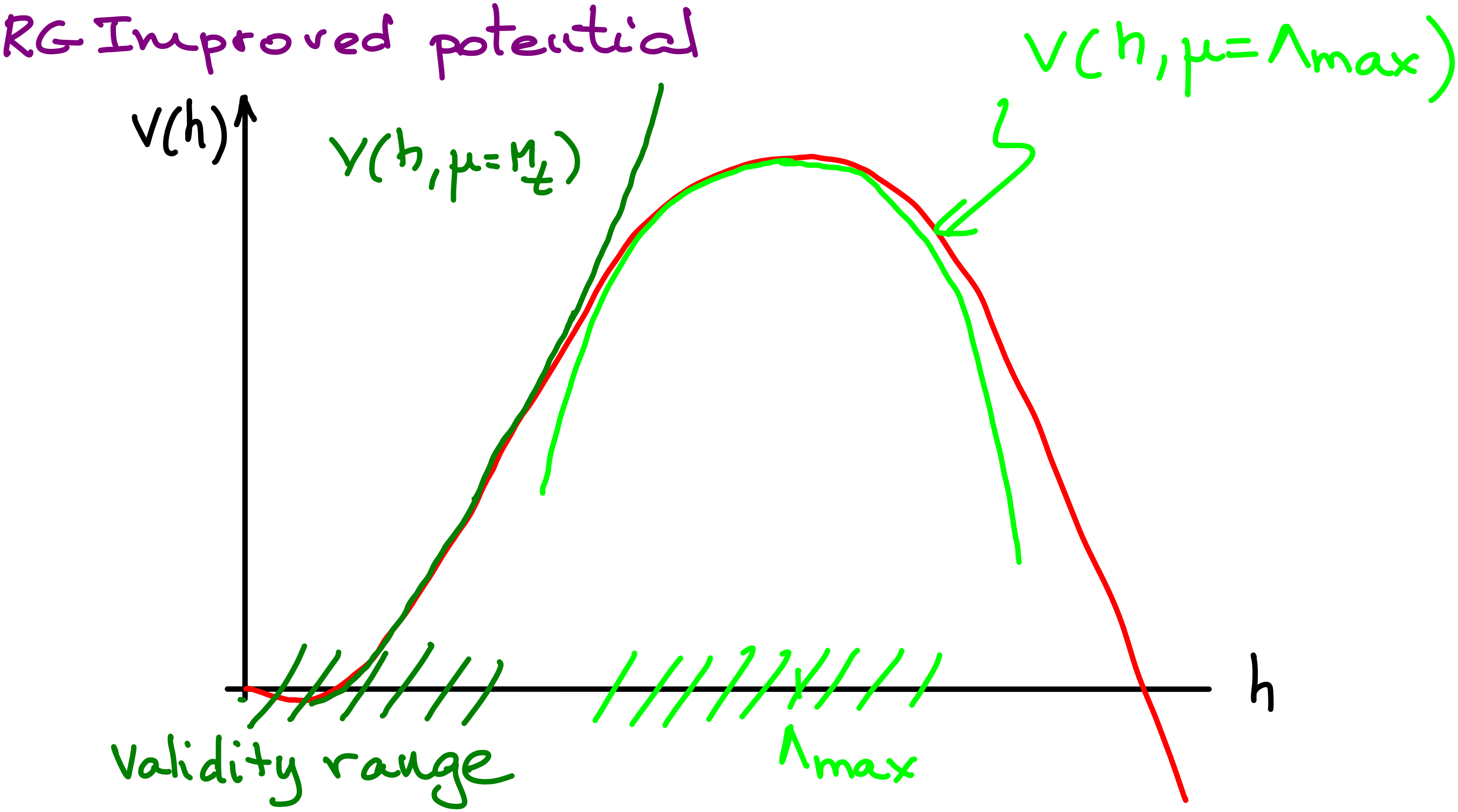
- 2-loop V_{eff} (Ford, Jack, Jones [hep-ph/0111190])
- 3-loop RGES (..., Chetyrkin, Zoller [hep-ph/1205.2892])
- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$
  (..., Shaposhnikov et al [hep-ph/1205,2893],
  , Degrassi et al [hep-ph/1205.6497])

Reduces theory error by a factor 3

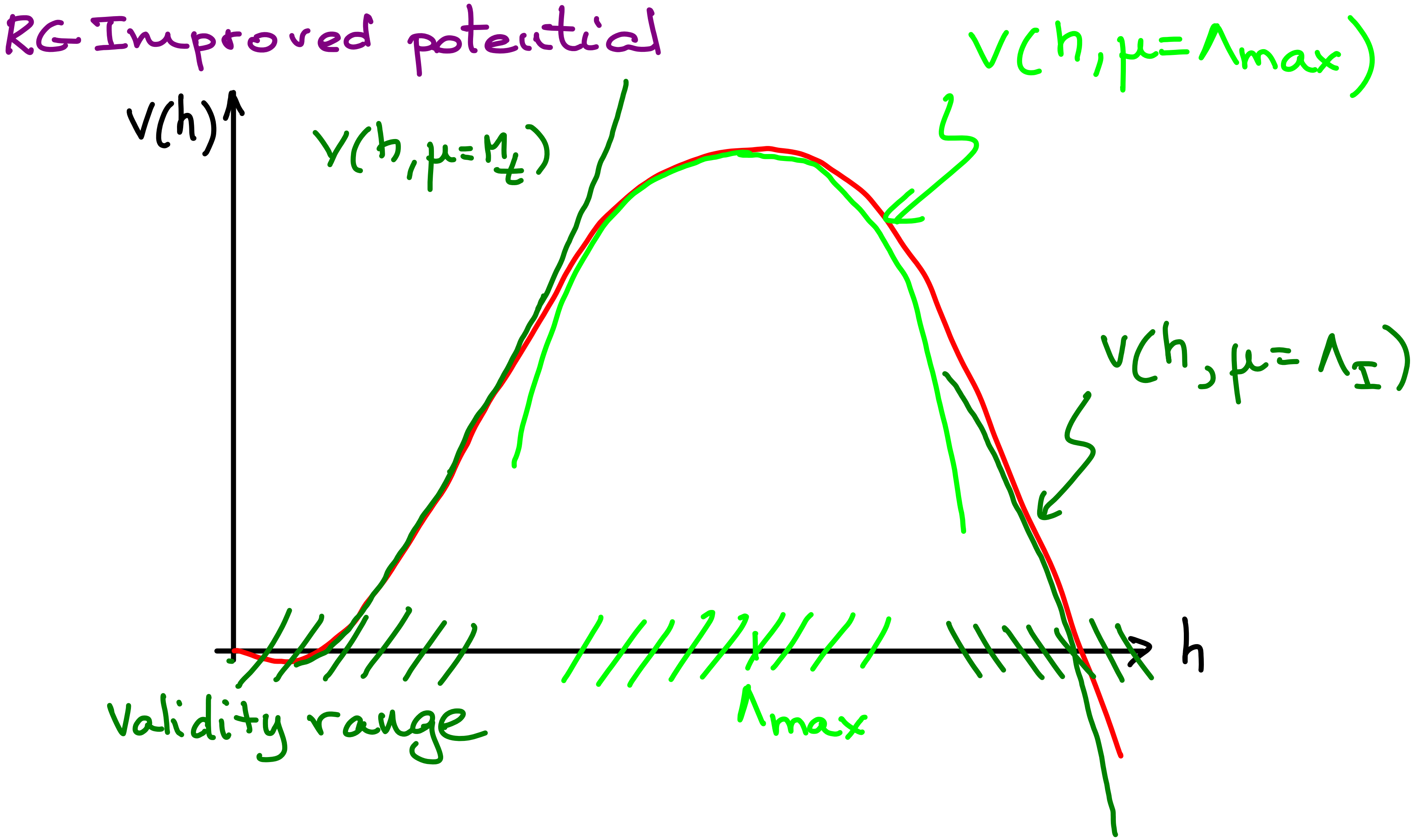
NNLO STABILITY BOUND



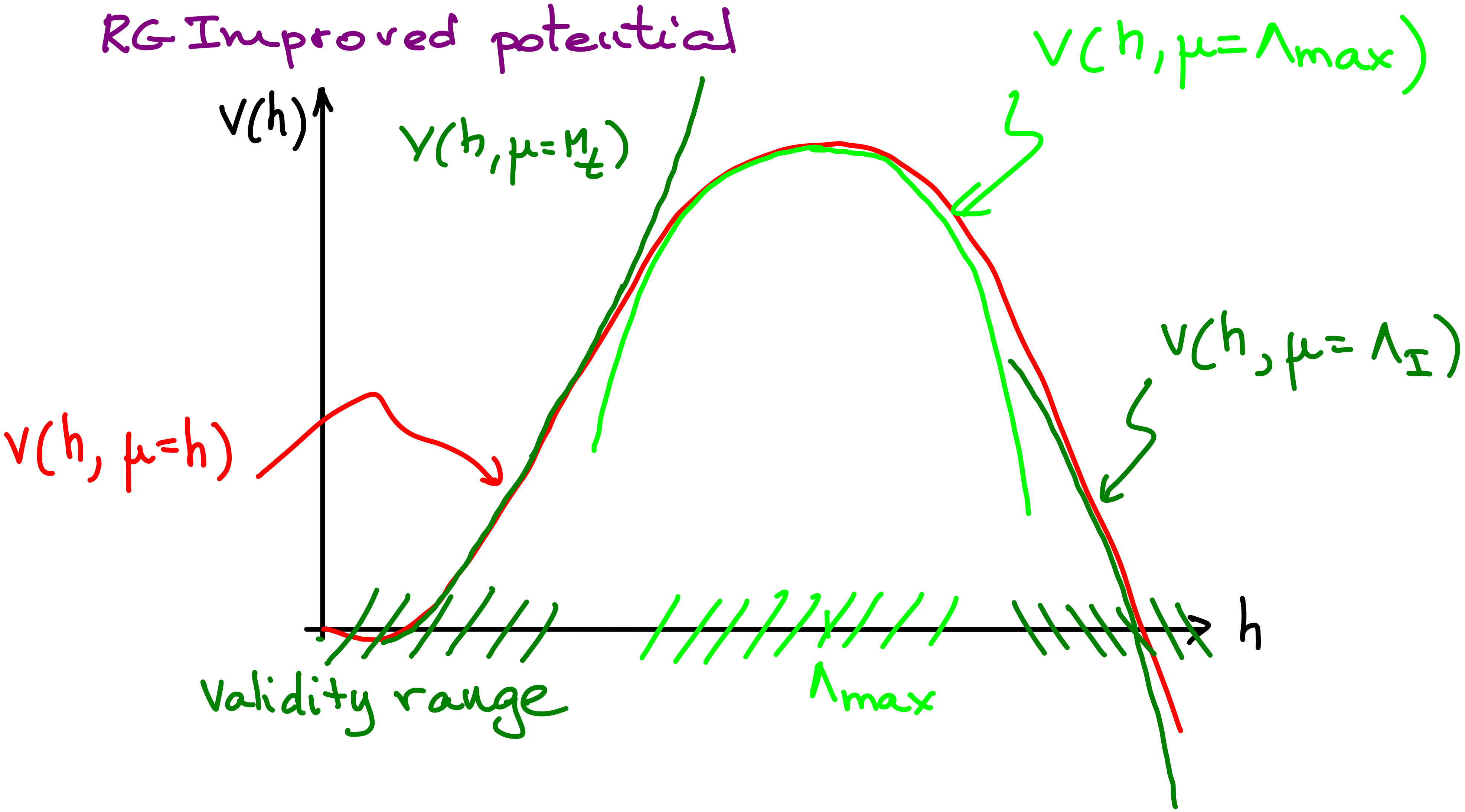
NNLO STABILITY BOUND



NNLO STABILITY BOUND

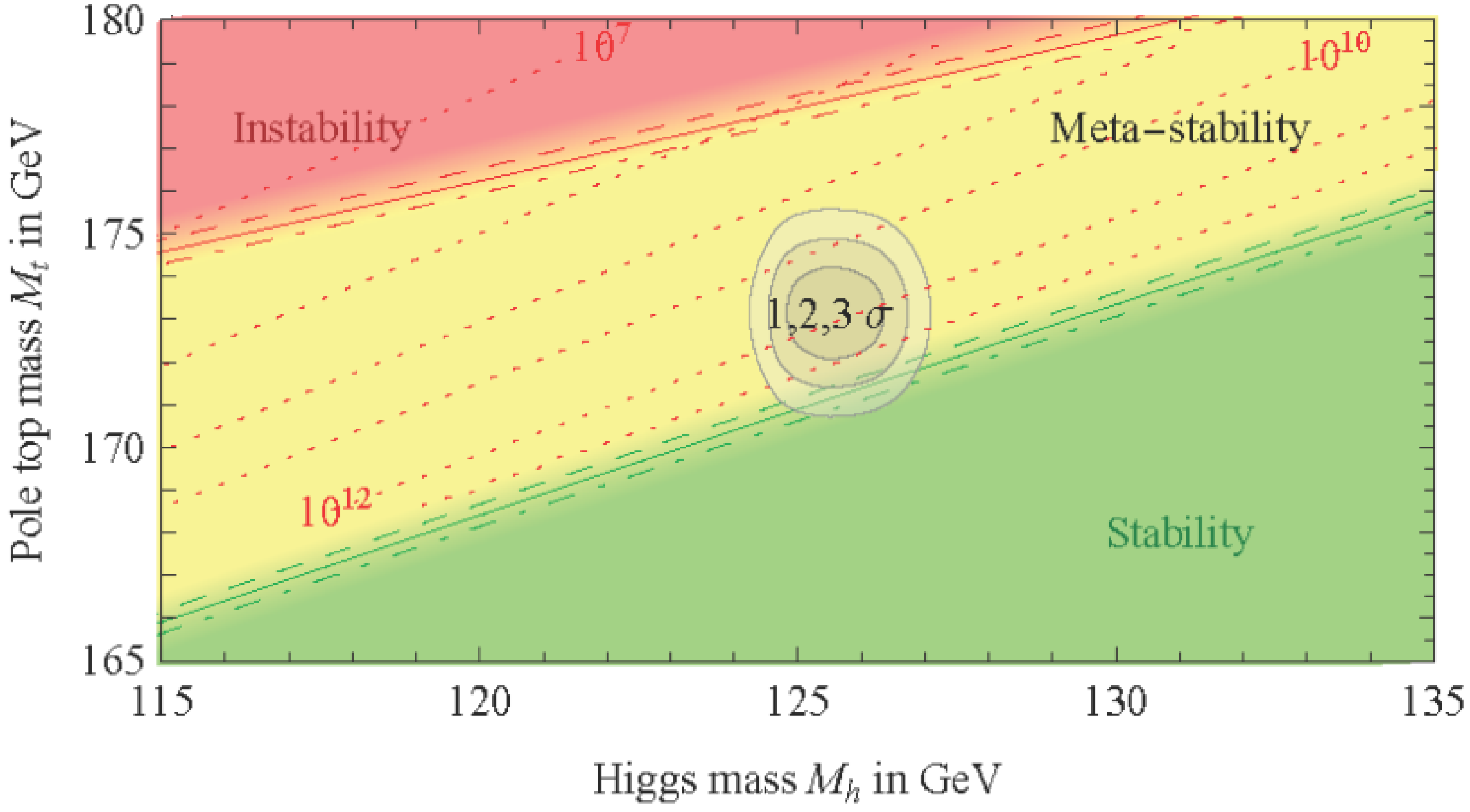


NNLO STABILITY BOUND



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

LIVING AT THE EDGE



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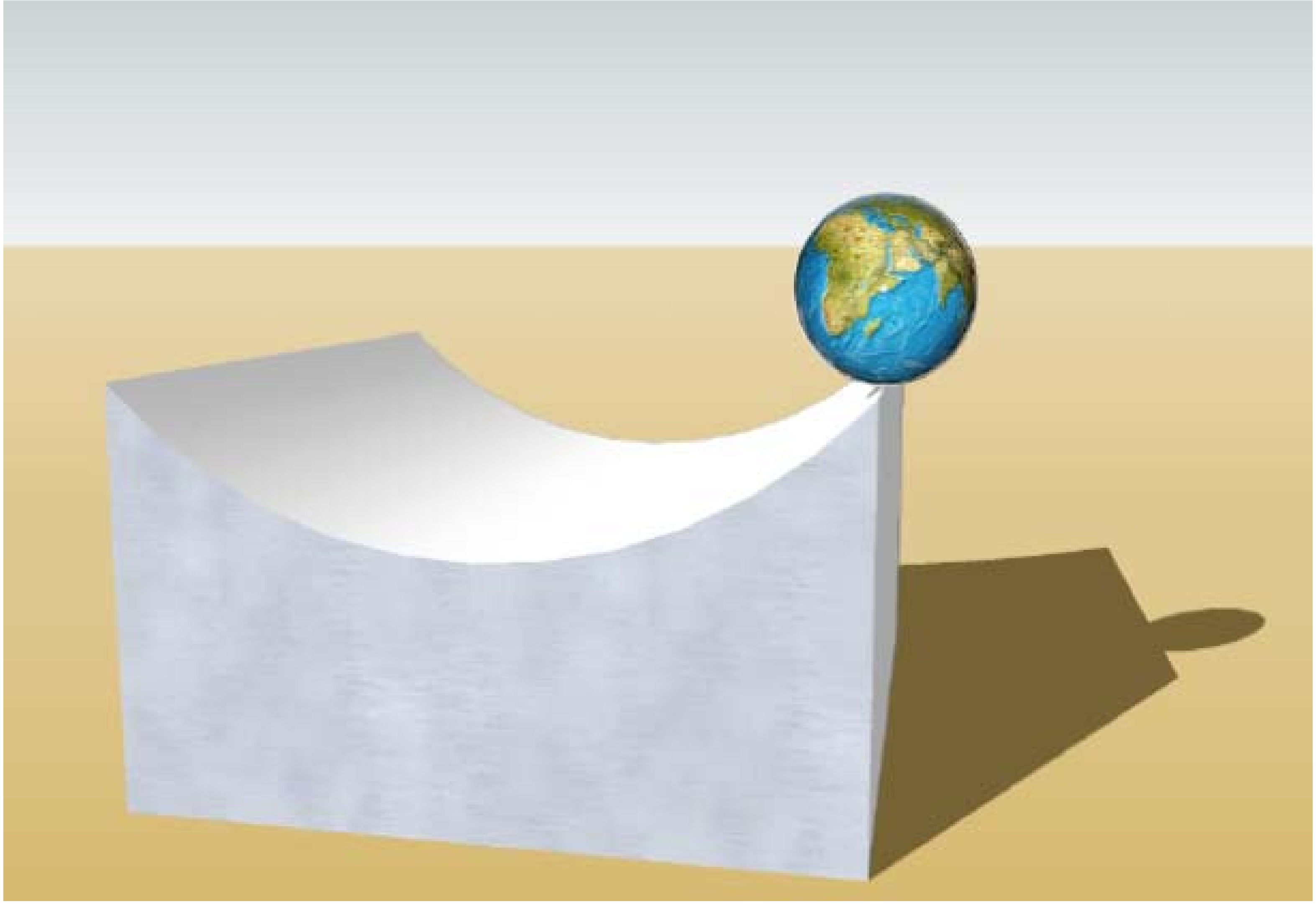
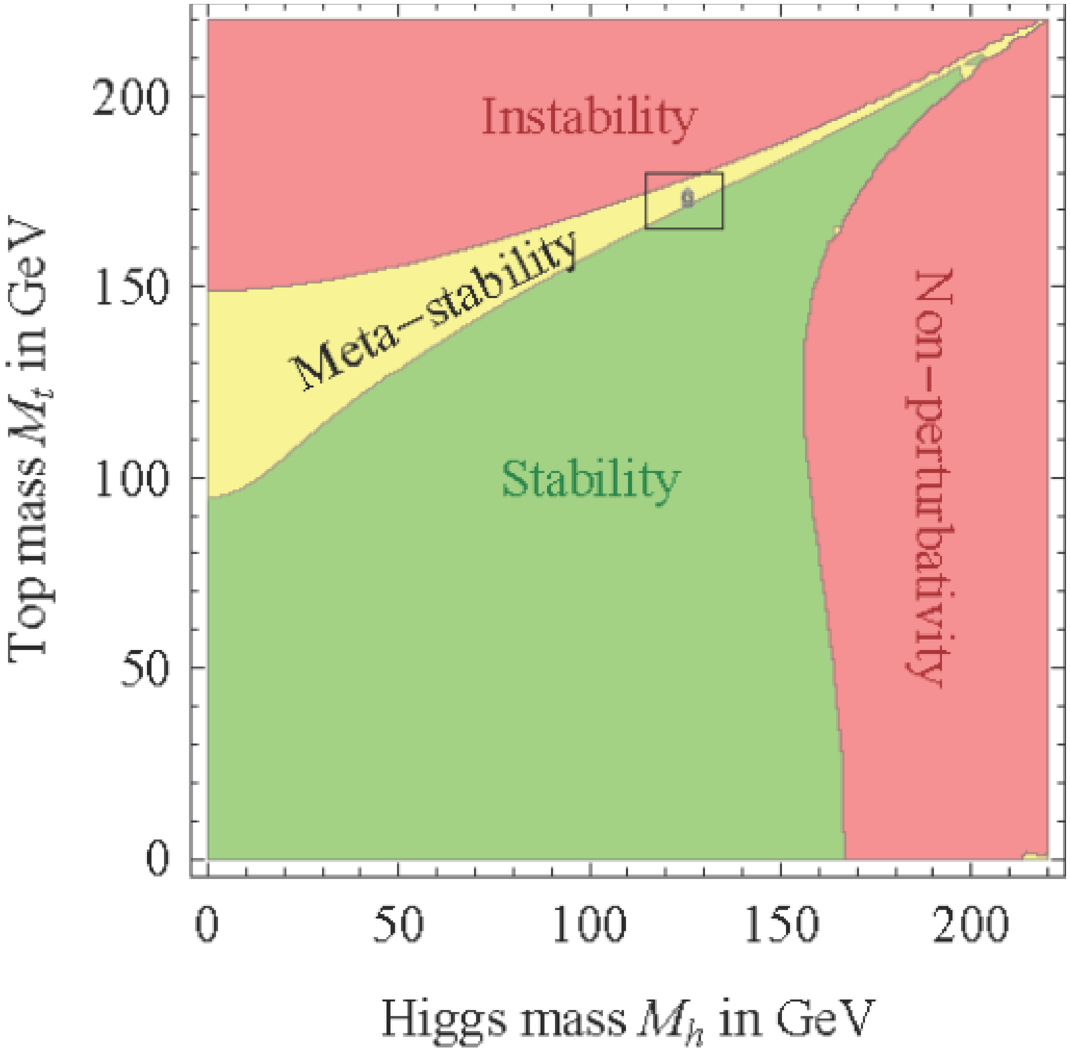


LIVING AT THE EDGE

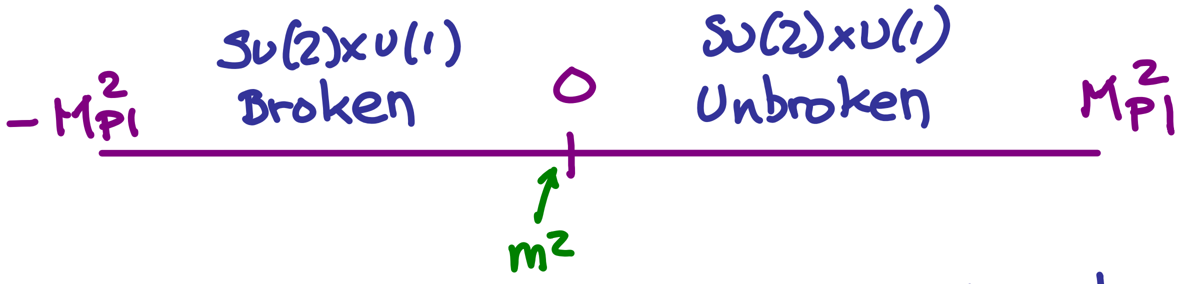


NEW KNOWLEDGE BRINGS NEW QUESTIONS

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

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

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

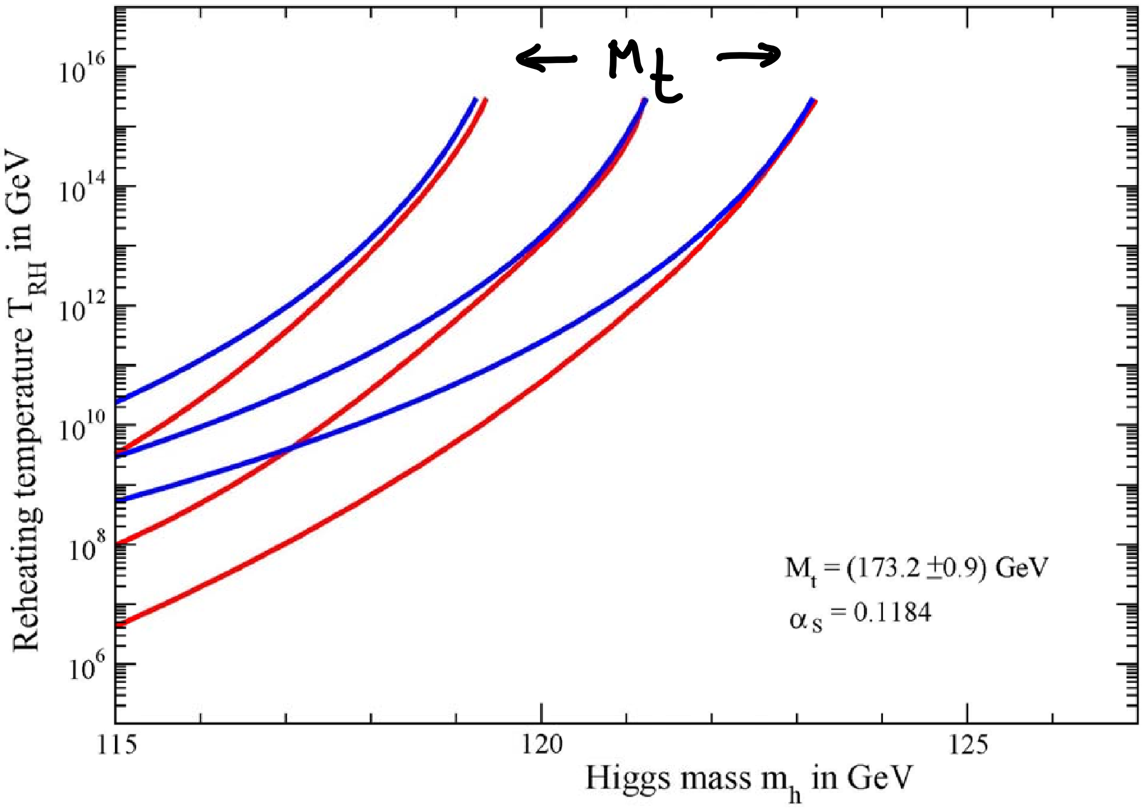


- Is the EW scale determined by Planck scale physics?
- Or is this just a coincidence? BSM...

OTHER IMPLICATIONS

- Cosmology :

Thermal fluctuations can induce vacuum decay



Bound on T_{RH} ?

OTHER IMPLICATIONS

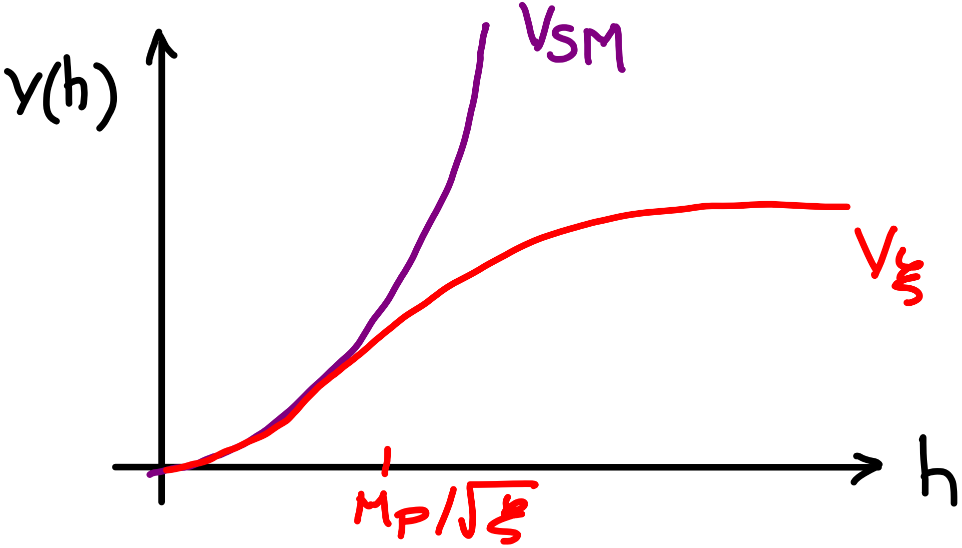
- Cosmology : Higgs inflation   Bezrukov, Shaposhnikov '07

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

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

rescales the potential as

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



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. Barbón, JRE '09

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

Requires marginal values of M_h & M_t

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

BSM & STABILITY

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	Example
IRRELEVANT	See-saw neutrinos
MAKE IT WORSE	See-saw neutrinos
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BSM & STABILITY

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	Example
IRRELEVANT	See-saw neutrinos
MAKE IT WORSE	See-saw neutrinos
CURE IT	See-saw neutrinos

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

Example

IRRELEVANT

See-saw neutrinos

$M_R \lesssim 10^{13}\,\mathrm{GeV}$

MAKE IT WORSE

See-saw neutrinos

$M_R \gtrsim 10^{13}\,\mathrm{GeV}$

CURE IT

See-saw neutrinos

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

OTHER IMPLICATIONS

- See-saw neutrinos: Impact on $\beta_\lambda \supset -y_\nu^4/(16\pi^2)$ *

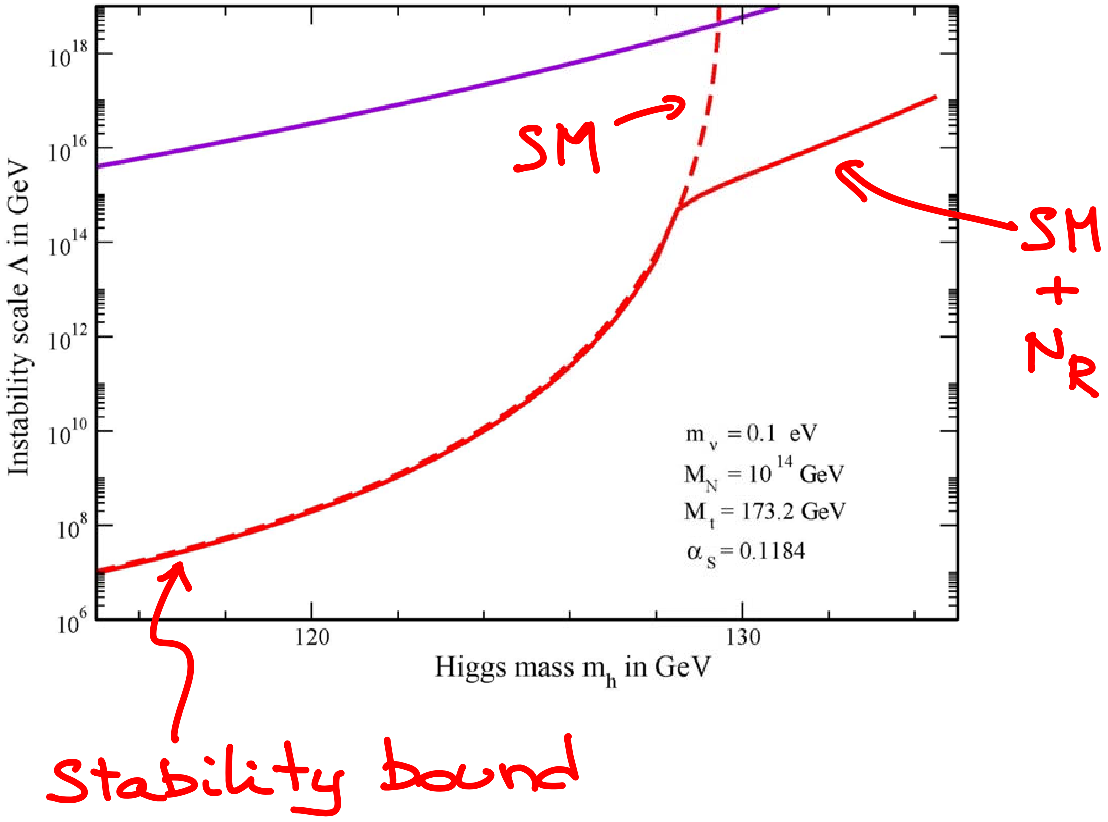
$$m_\nu \sim \frac{y_\nu^2 v^2}{M_R}$$

$$M_R \uparrow \Rightarrow y_\nu \uparrow$$

⇧

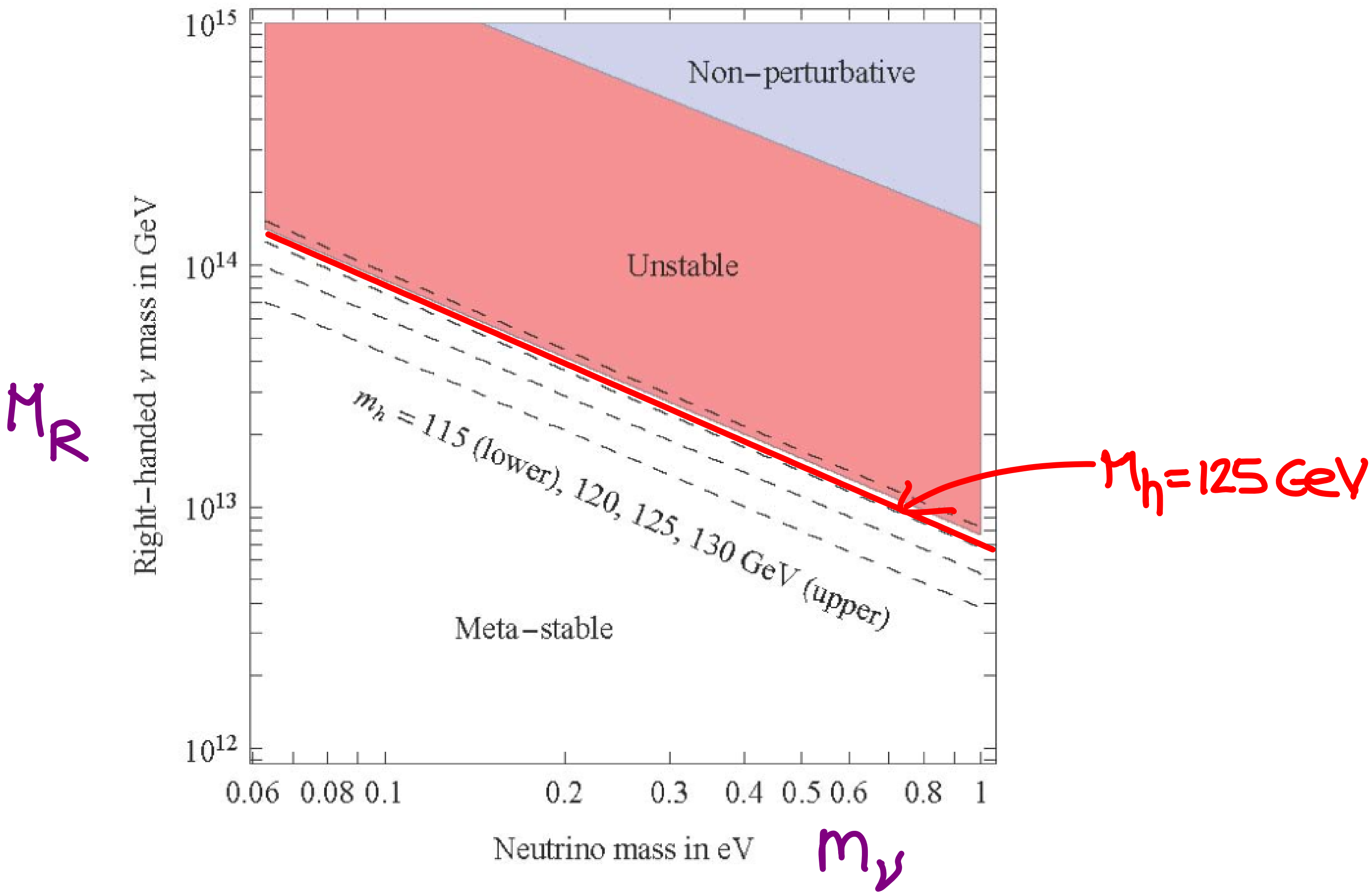
Adds to the top destabilizing effect

$M_R = 10^{14}$ GeV



OTHER IMPLICATIONS

- See-saw neutrinos: Bound on M_{ν_R}



SIMPLE VACUUM STABILIZATION

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

Ingredients :

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

(we will assume $w \gg v$)

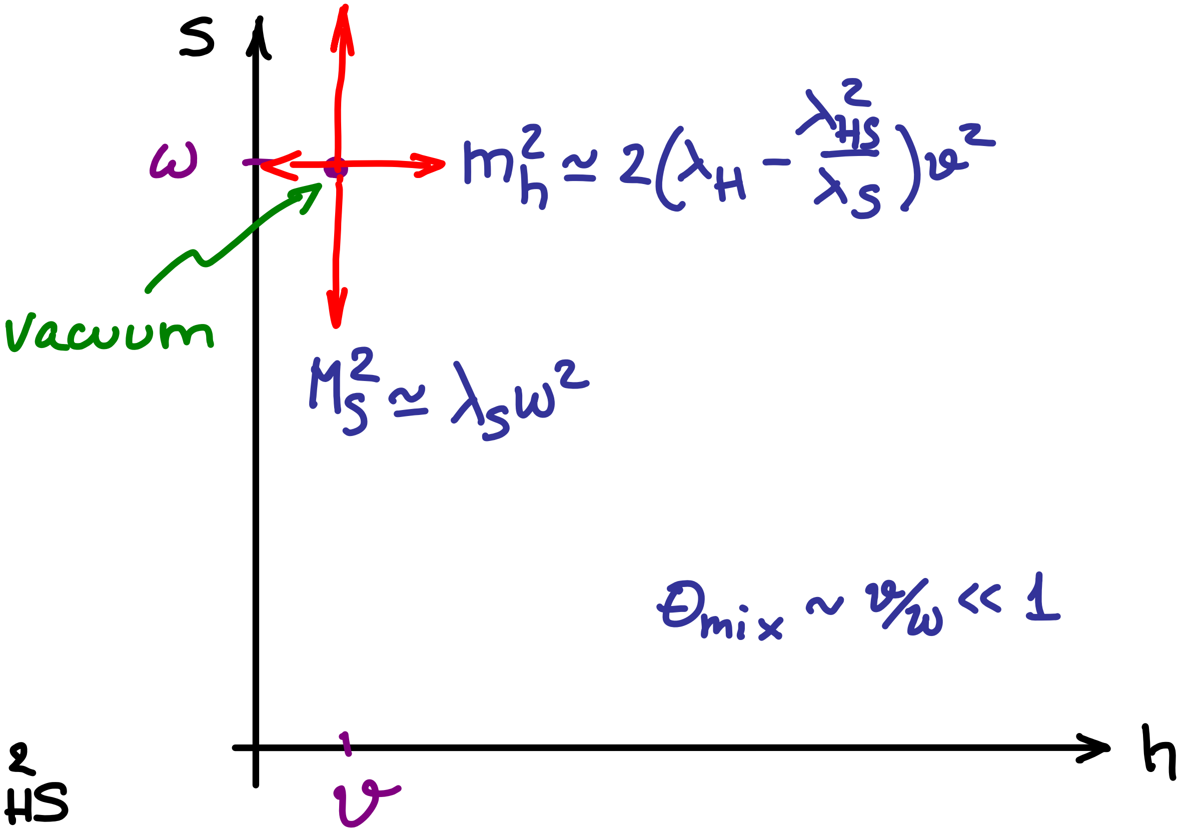
MODEL STRUCTURE

Potential:

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

Spectrum:

$$M^2 = 2 \begin{pmatrix} \lambda_H v^2 & \lambda_{HS} v w \\ \lambda_{HS} v w & \lambda_S w^2 \end{pmatrix}$$



LOW-ENERGY THEORY

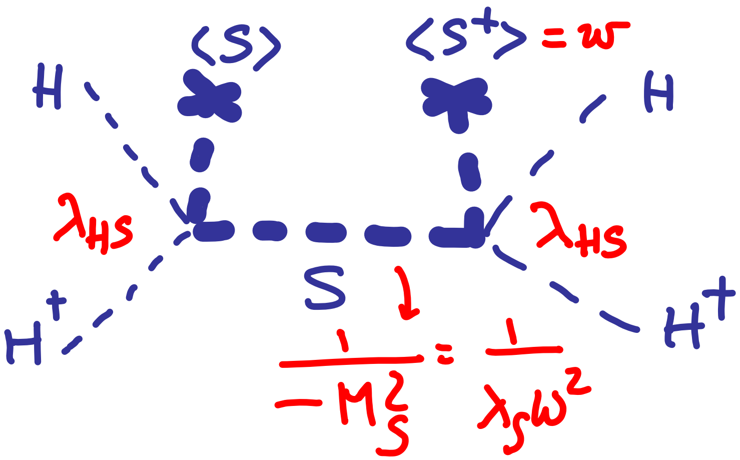
Integrating out S ⇒ Below M_S : SM

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

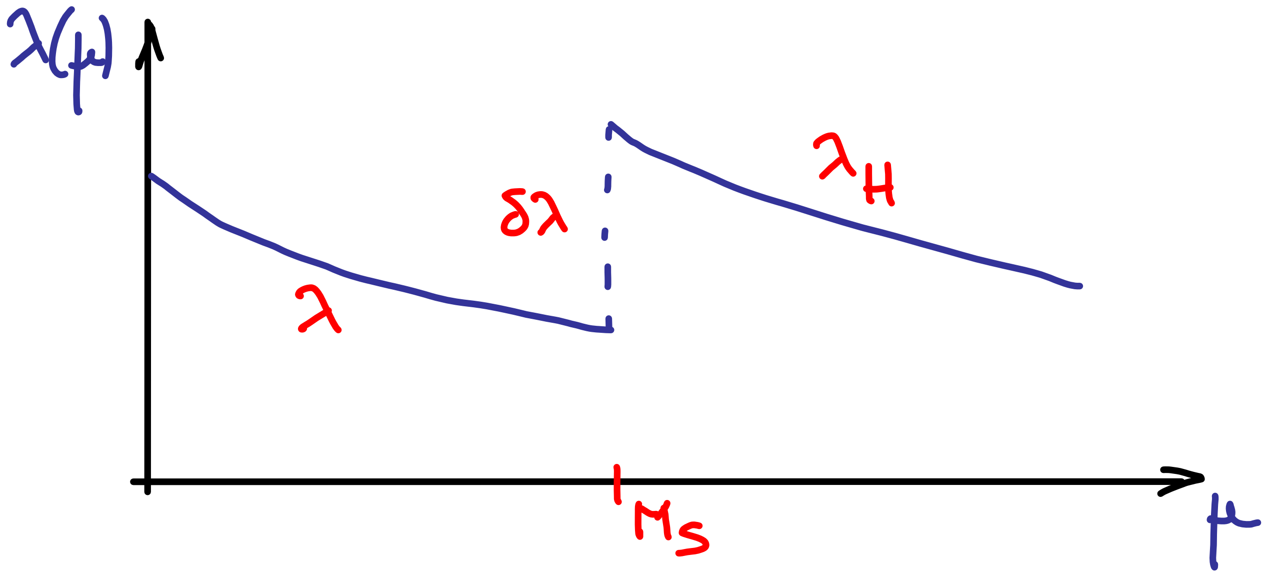
$$\downarrow$$

$$\underbrace{\lambda_H}_{\text{original } h \text{ quartic}} - \underbrace{\frac{\lambda_{HS}^2}{\lambda_S}}_{\text{tree-level threshold correction}}$$

Diagrammatically



CRUCIAL THRESHOLD CORRECTION



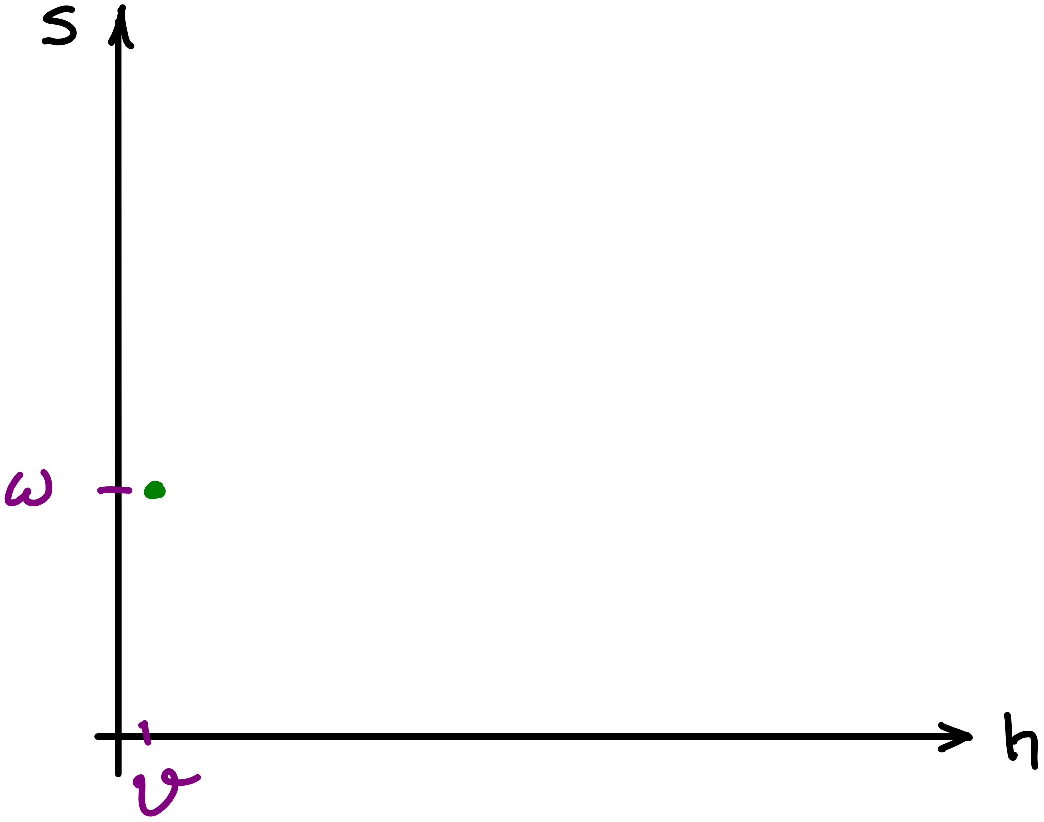
Matching at M_S : $\lambda(M_S) = \lambda_H(M_S) - \delta\lambda$

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

But, we must look more closely to stab. conditions

STABILITY CONDITIONS

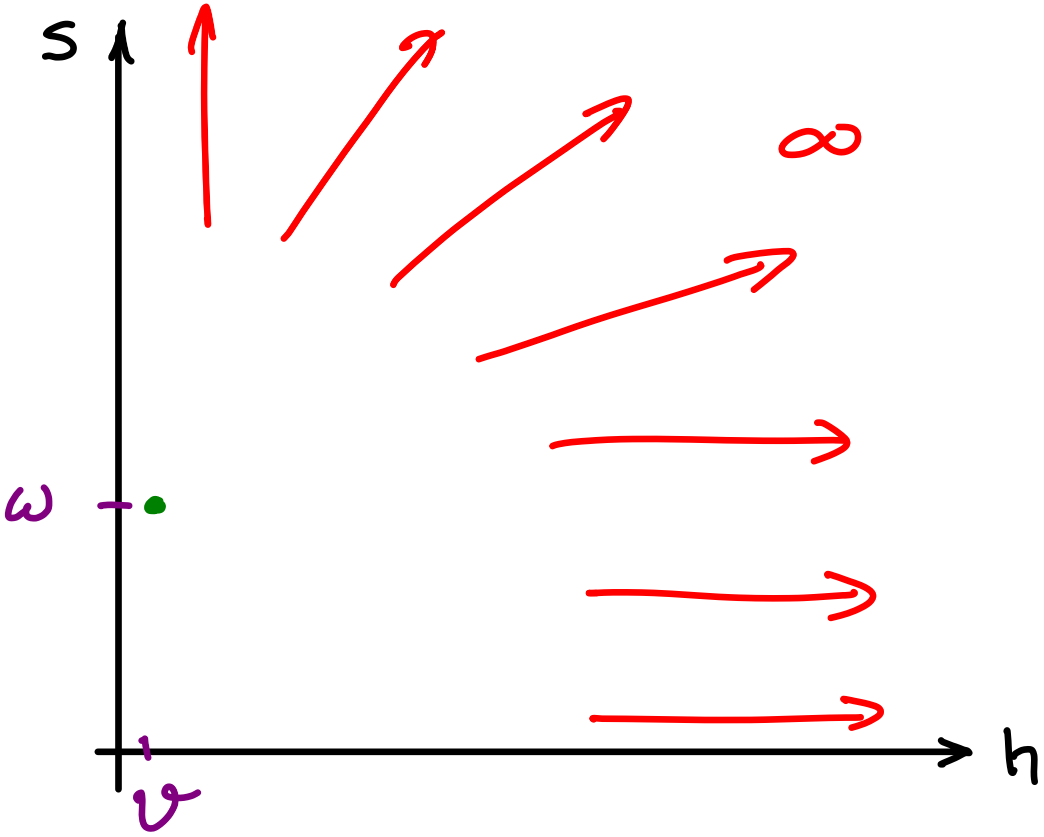
$$V = \lambda_H \left(|H|^2 - v^2/2\right)^2 + \lambda_S \left(S^\dagger S - \omega^2/2\right)^2 +$$
$$+ 2\lambda_{HS} \left(|H|^2 - v^2/2\right)\left(S^\dagger S - \omega^2/2\right)$$



STABILITY CONDITIONS

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

Large
field
values



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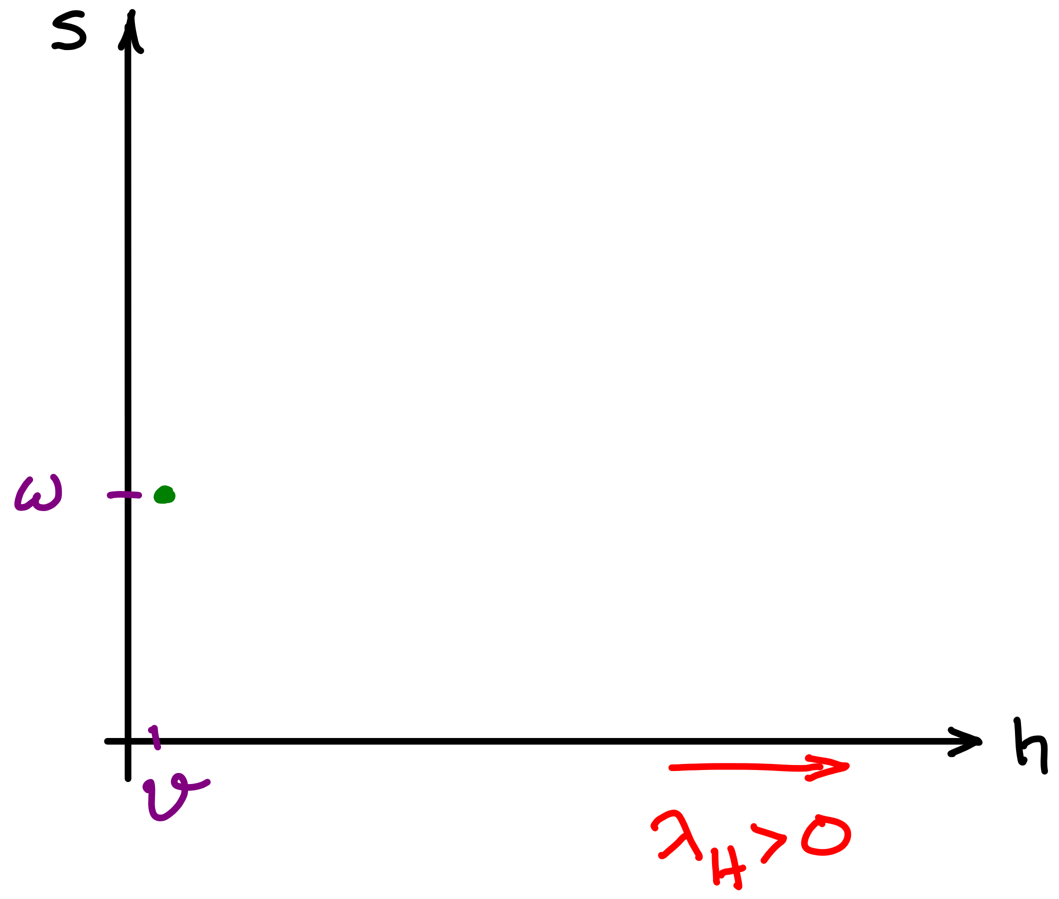

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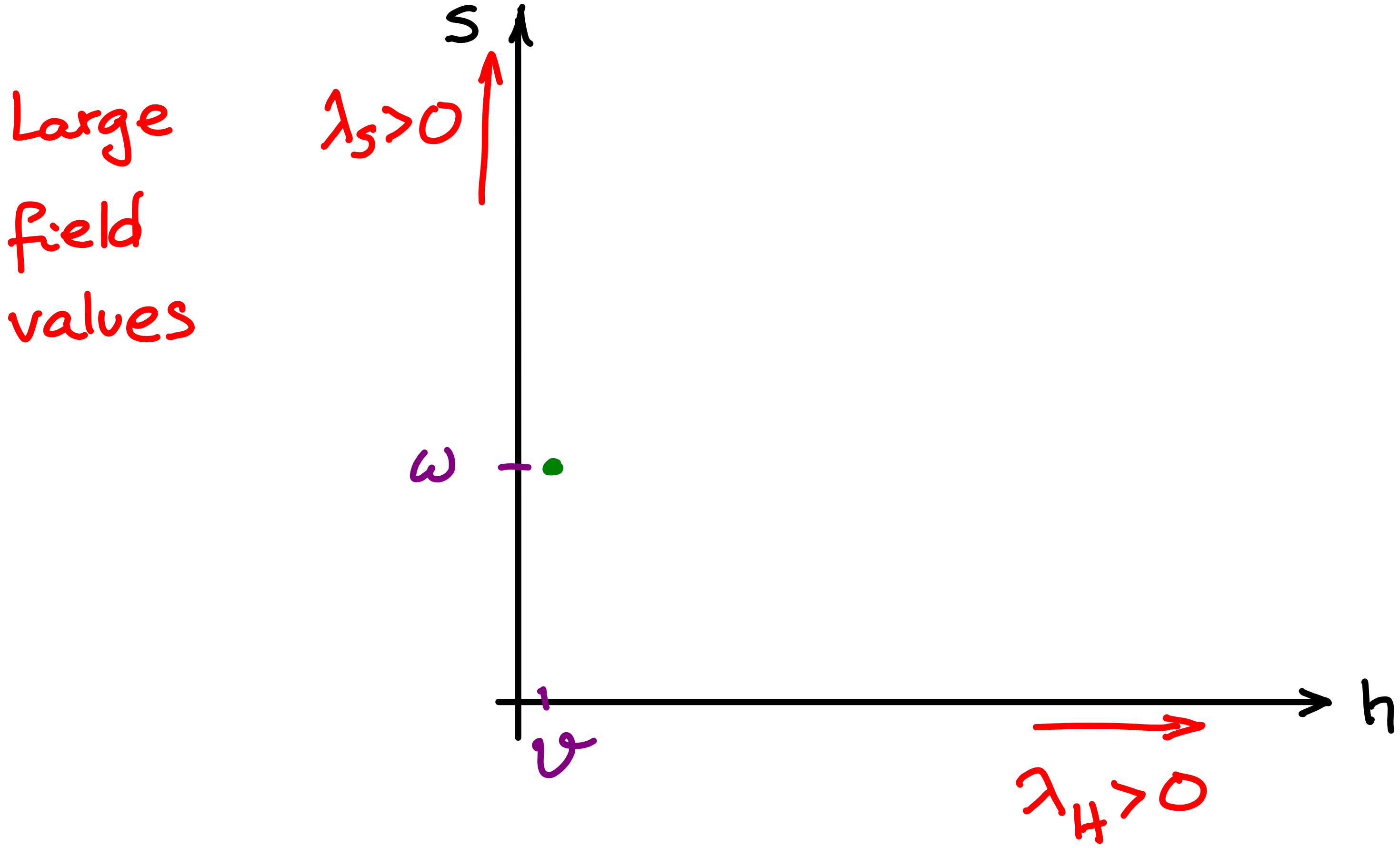

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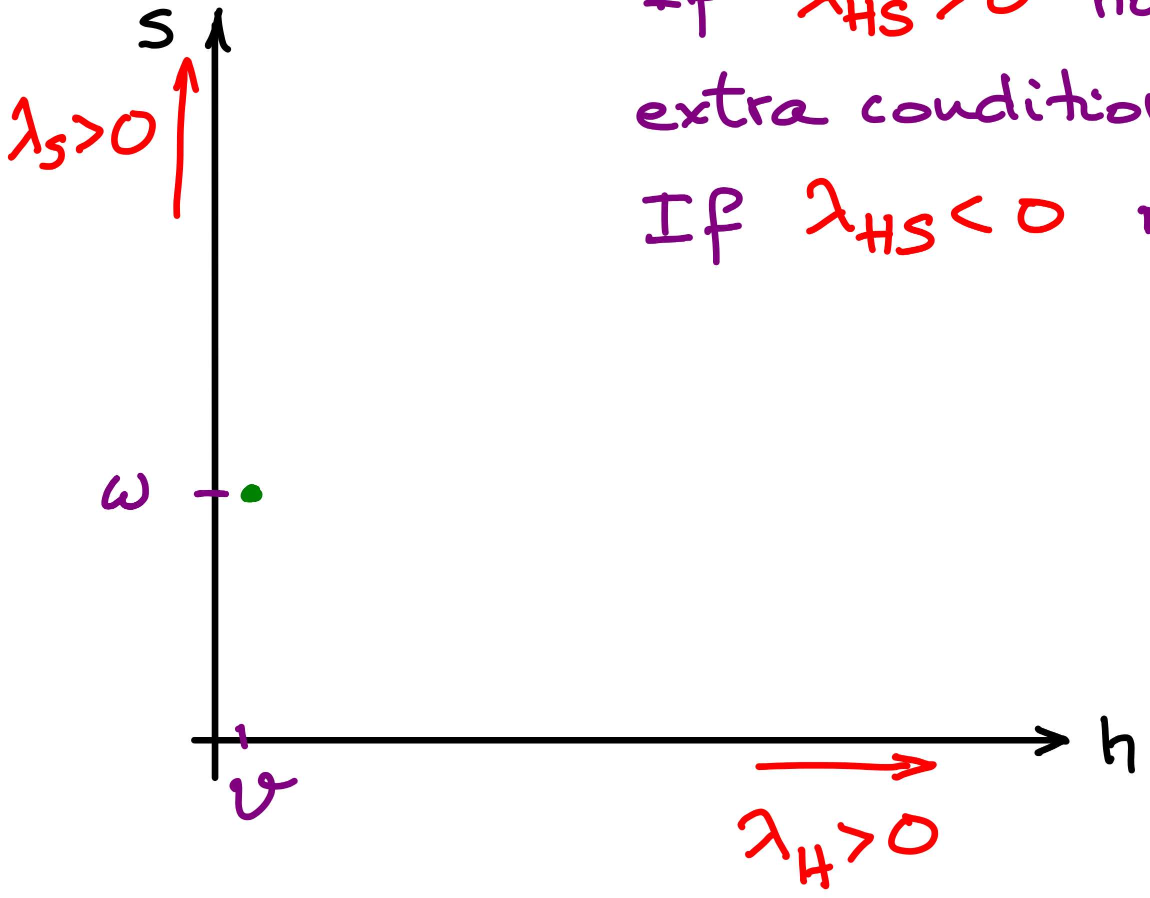
Large field values



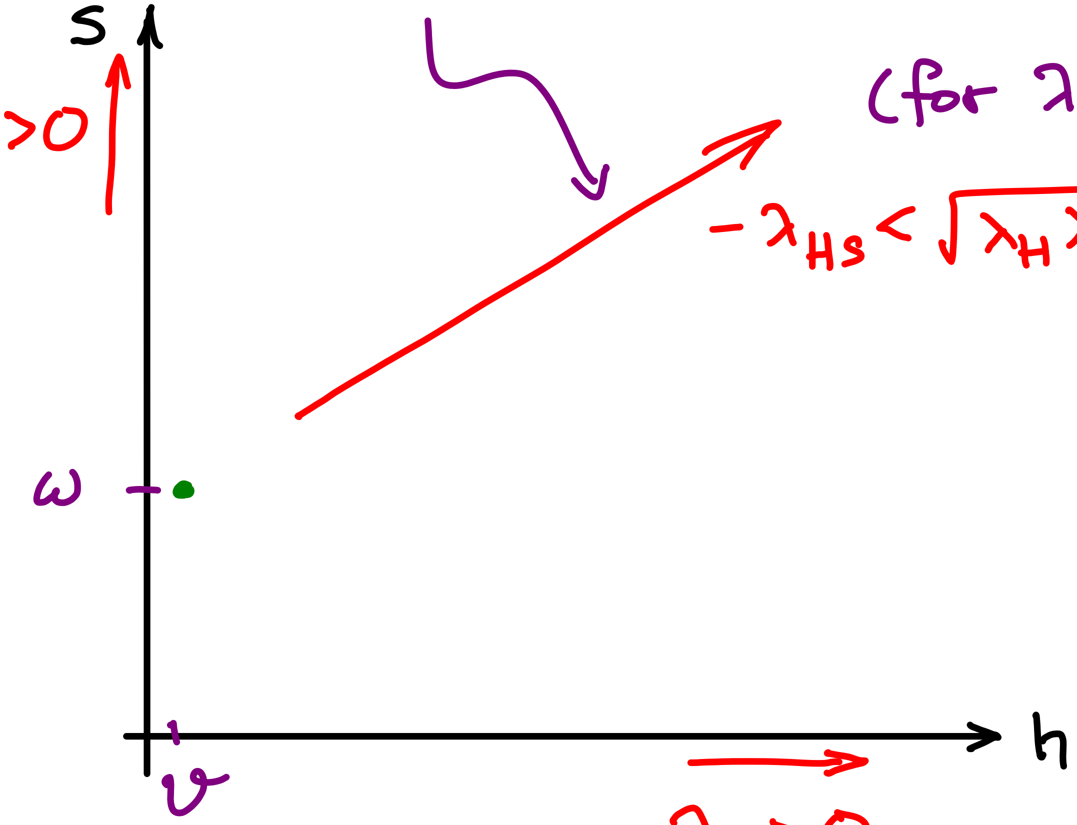
If $\lambda_{HS}>0$ no extra condition.

If $\lambda_{HS}<0$ ⇨

STABILITY CONDITIONS

$$V = \frac{1}{4\lambda_H}\left\{\underbrace{\left(\lambda_H|H|^2+\lambda_{HS}|S|^2\right)^2}_{\overset{\shortparallel}{0}} + \left(\lambda_S\lambda_H - \lambda_{HS}^2\right)|S|^4\right\}$$

Large field values



$\lambda_S > 0$

(for $\lambda_{HS} < 0$ only)

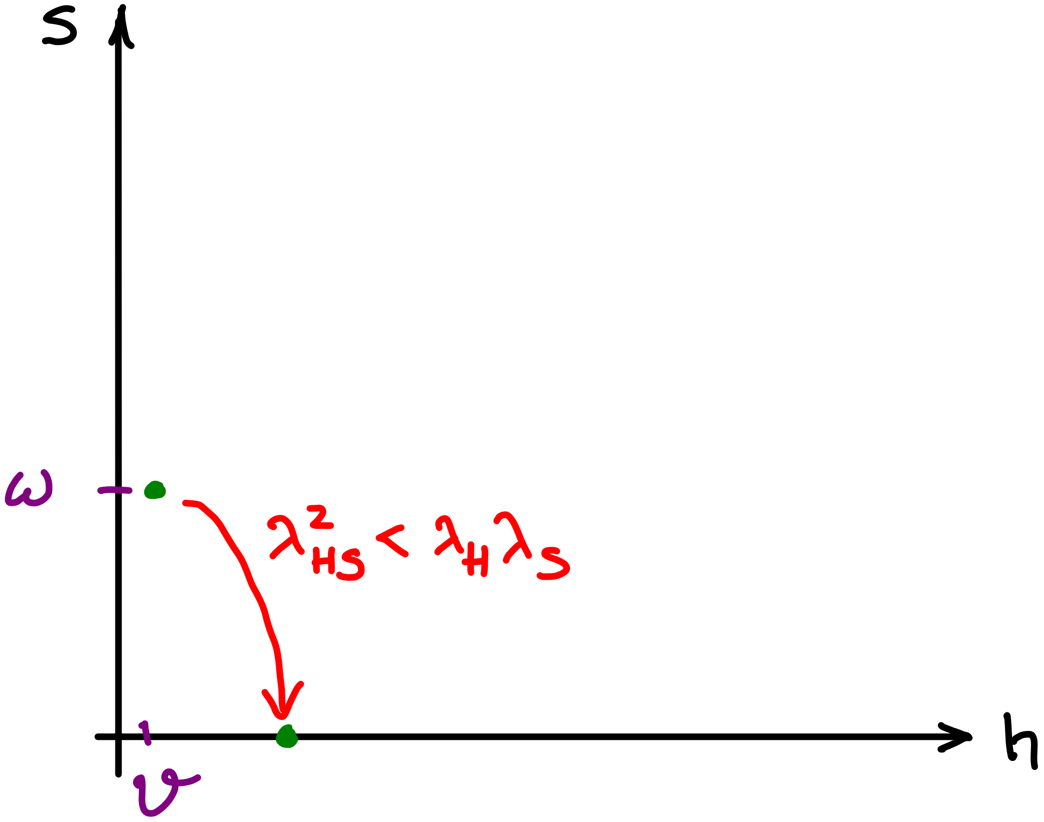
$-\lambda_{HS} < \sqrt{\lambda_H \lambda_S}$

$\lambda_H > 0$

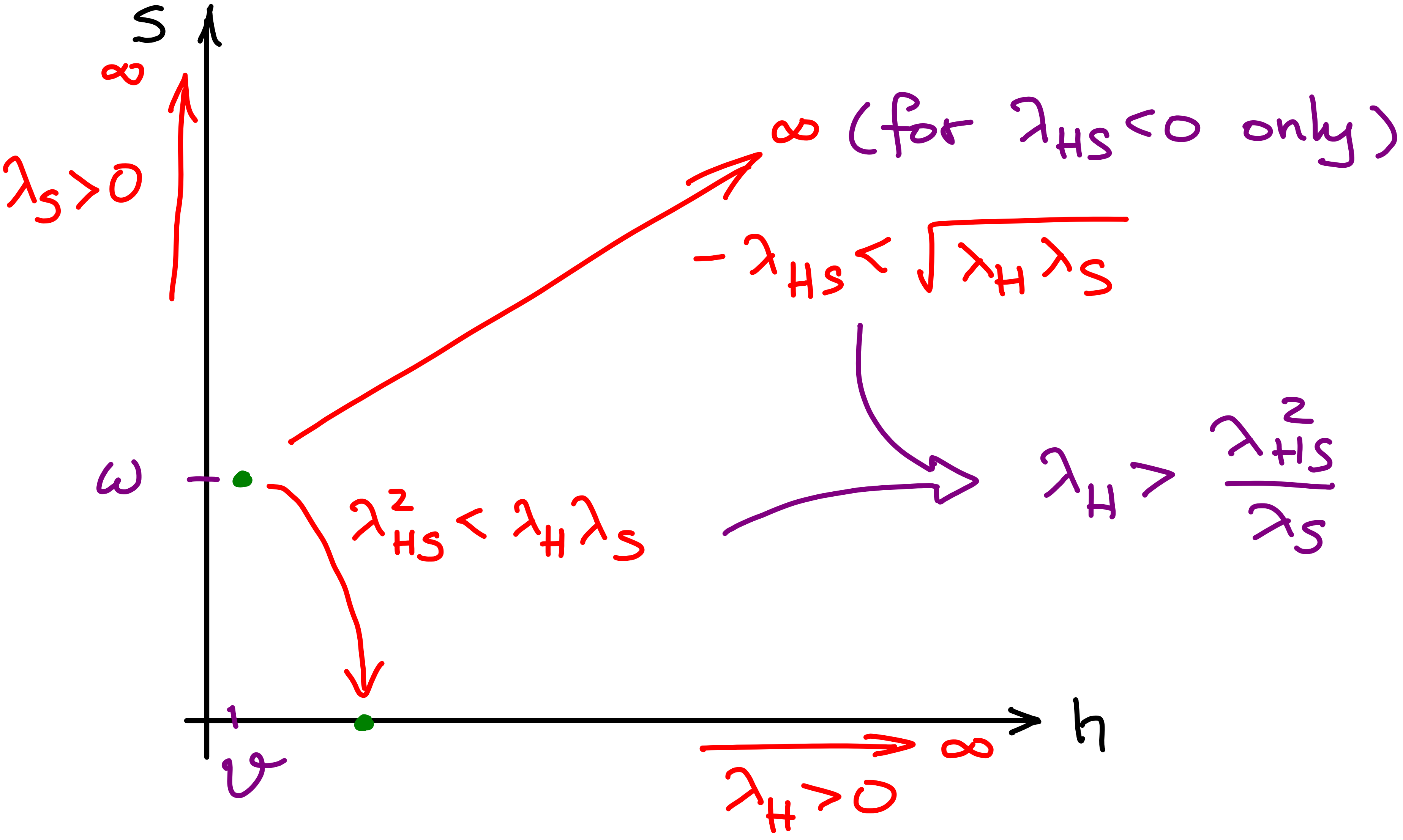
STABILITY CONDITIONS

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

Tachyonic
Instability at
Low field
values



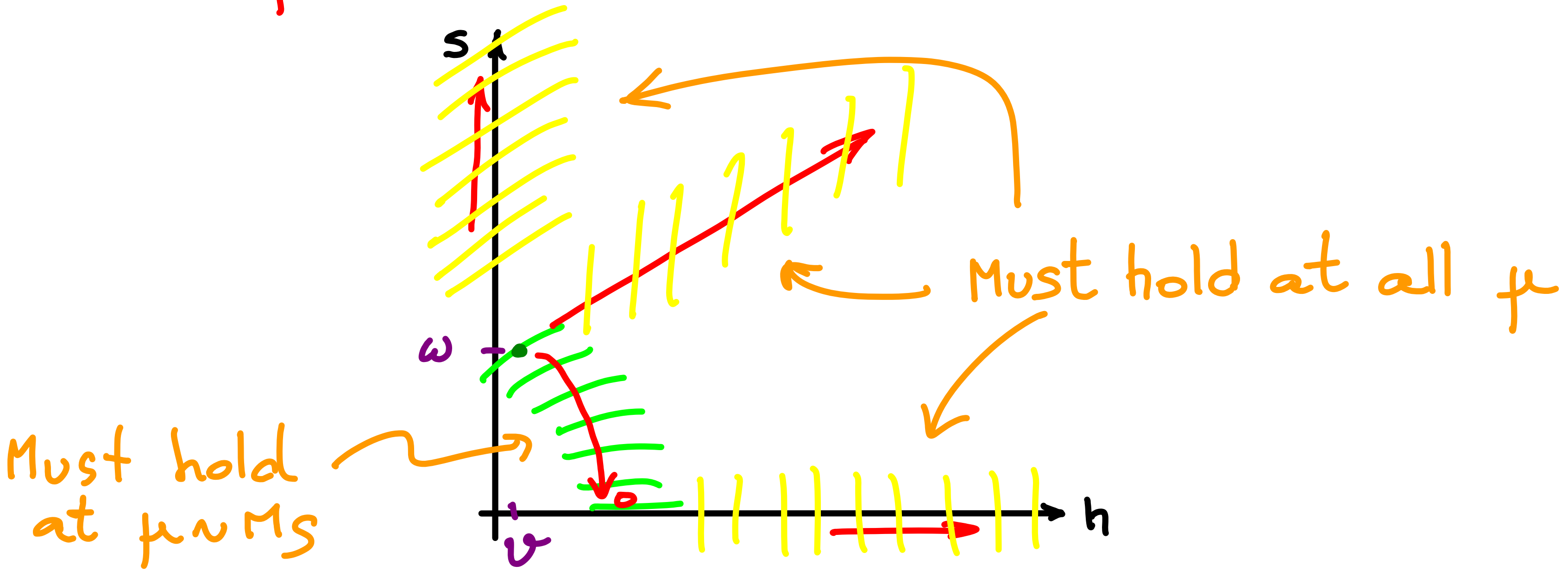
STABILITY CONDITIONS



CRUCIAL THRESHOLD CORRECTION

Stability condition $\lambda_H > \frac{\lambda_{HS}^2}{\lambda_S} = \delta\lambda$ shifted up by same amount as λ ! No gain ??

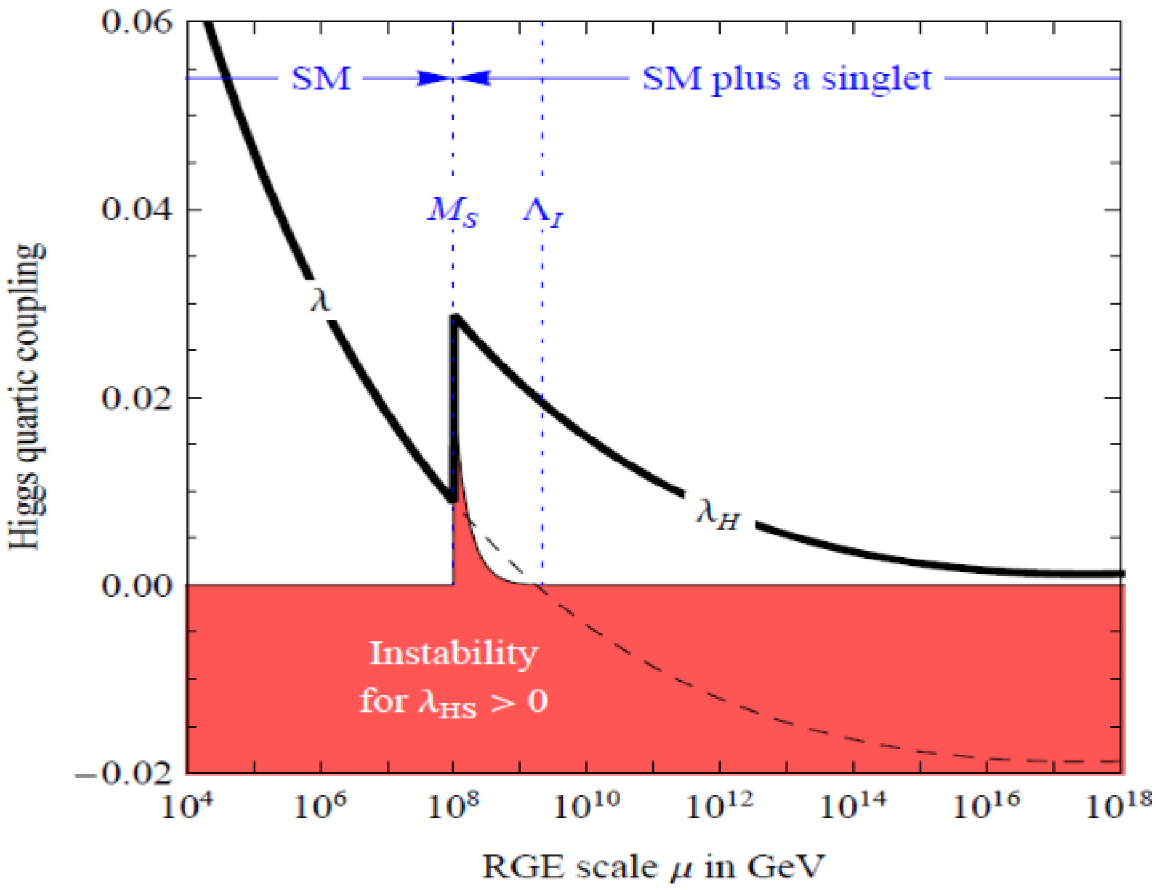
Scale-dependence is all-important in stab. conditions



$\lambda_{HS} > 0$

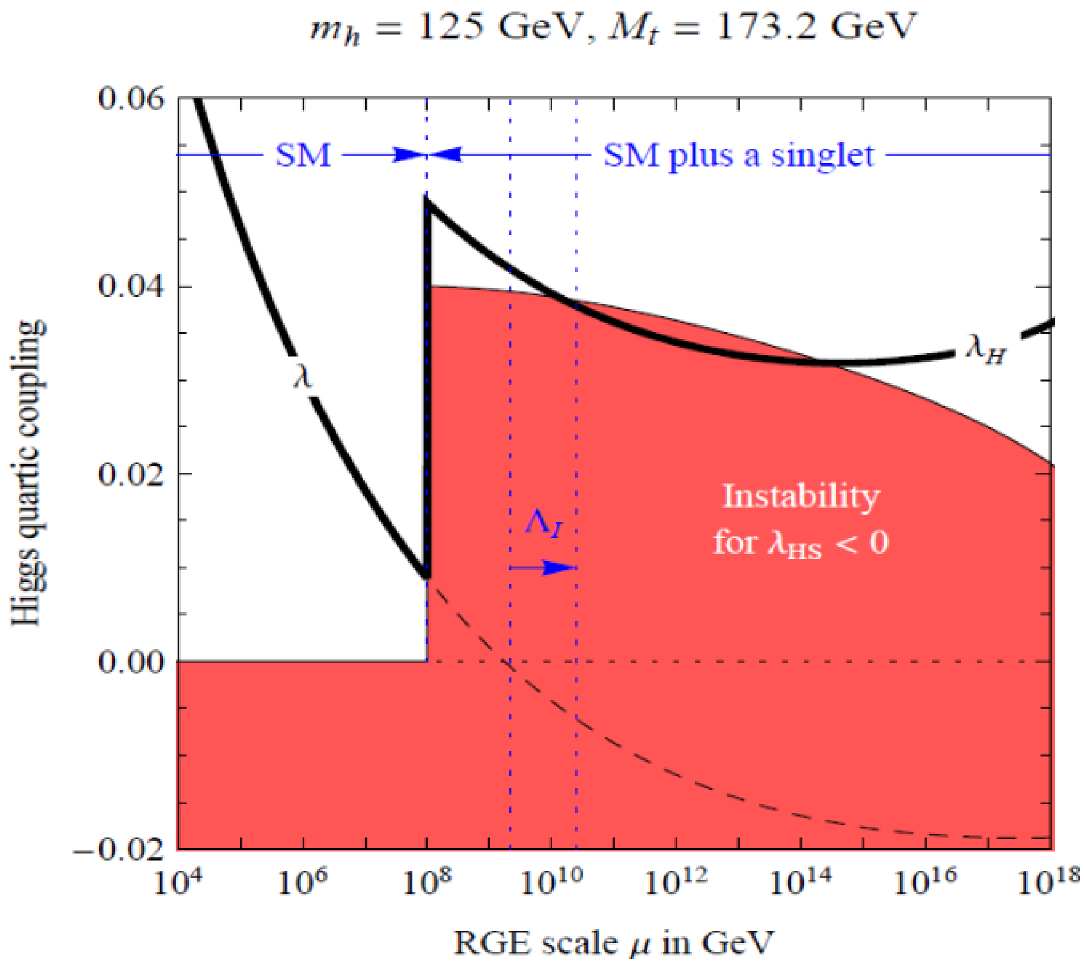
Need to enforce $\lambda_H > \lambda_{HS}^2/\lambda_S$ only at low-energy for $\mu \sim M_S$

$m_h = 125$ GeV, $M_t = 173.2$ GeV

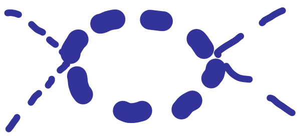


$\lambda_{HS} < 0$

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



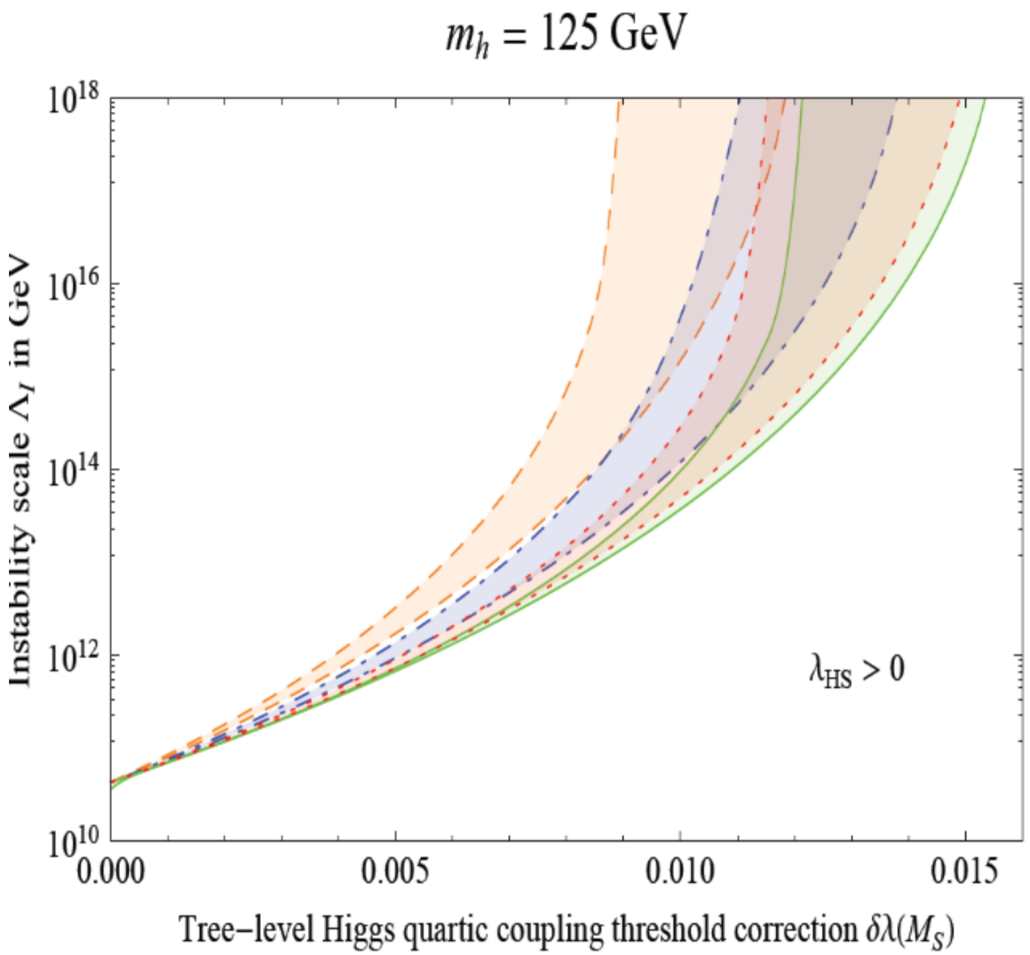
Effect now relies on loop effect



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

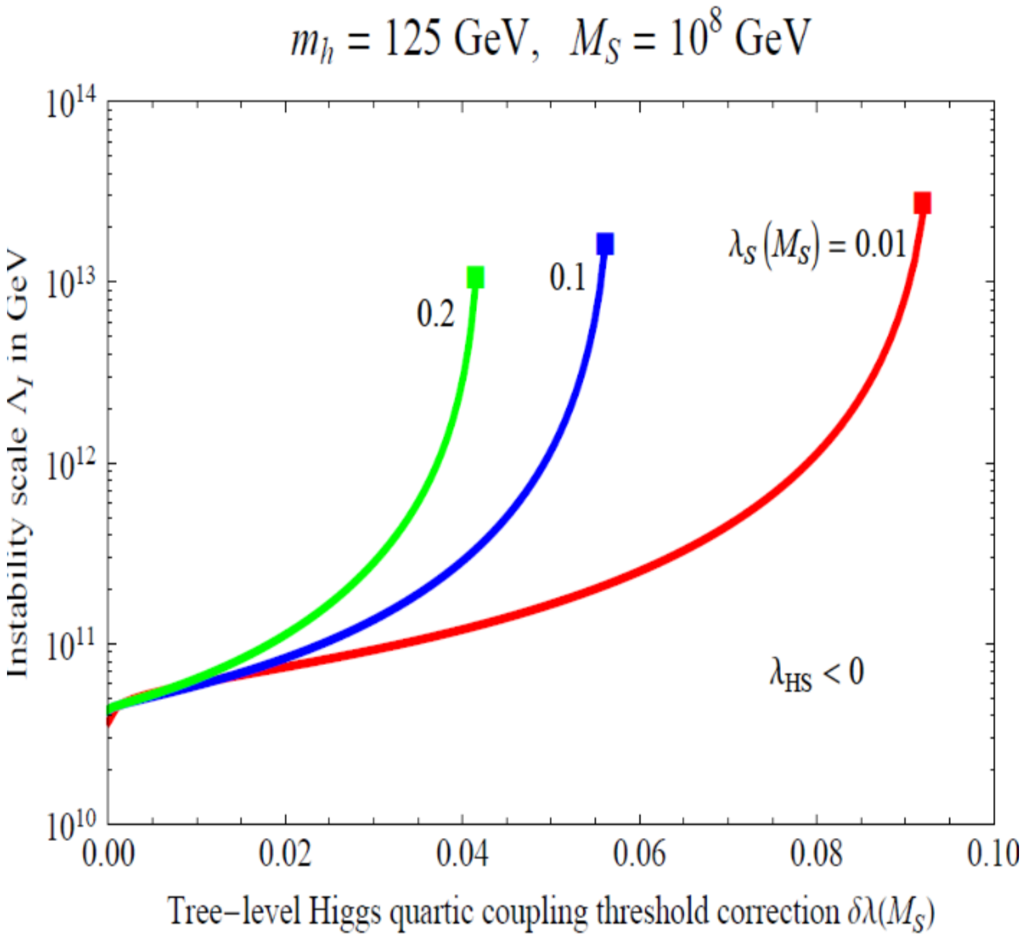
IMPACT ON INSTABILITY SCALE

$\lambda_{HS} > 0$



$\delta\lambda$

$\lambda_{HS} < 0$



$\delta\lambda$

IMPLEMENTATION IN MODELS

In our paper :

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

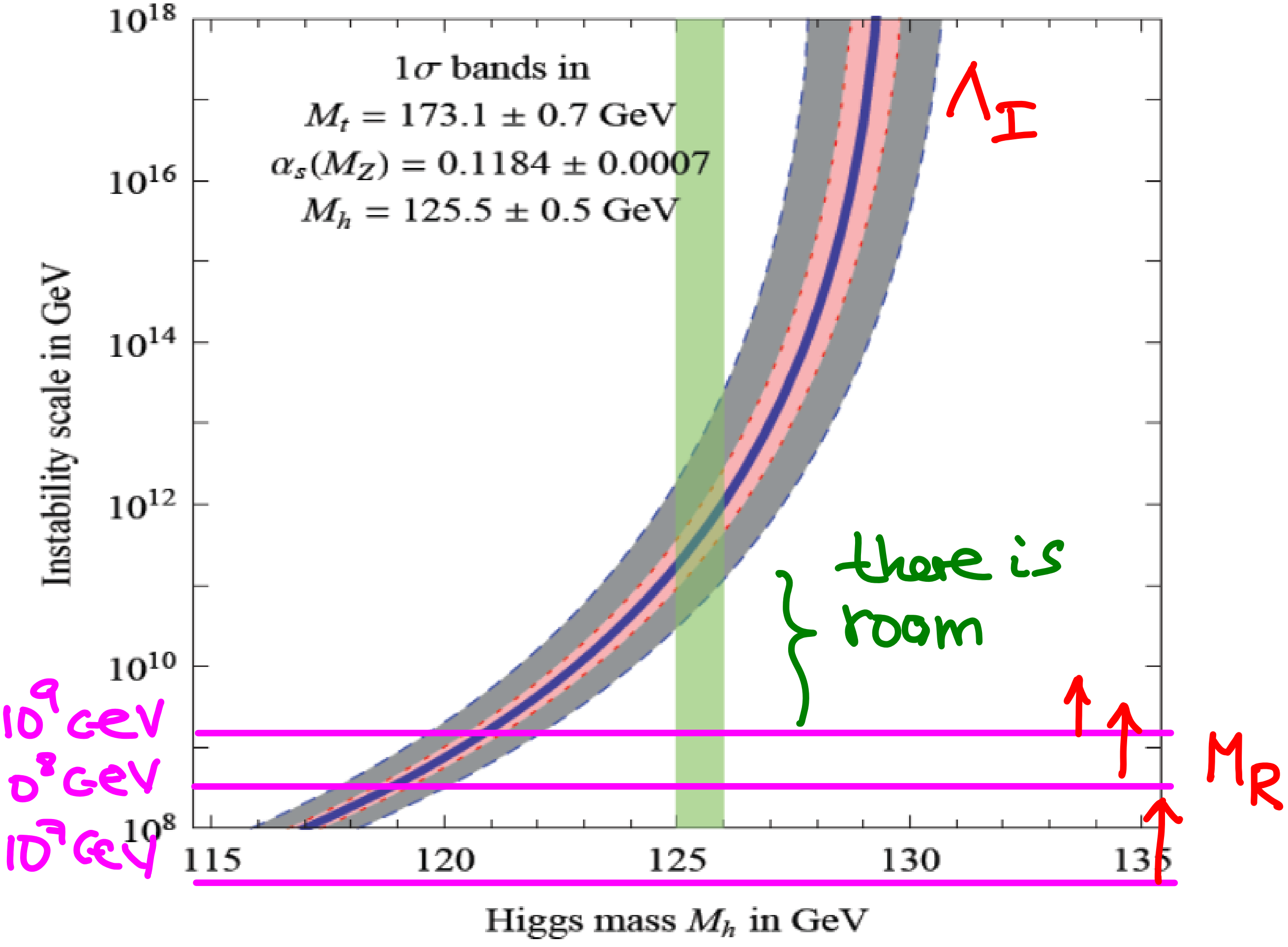
Later uses of the idea

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

SEE-SAW IMPLEMENTATION

Use S to generate the ν_R mass: $M_N \sim \langle S \rangle$

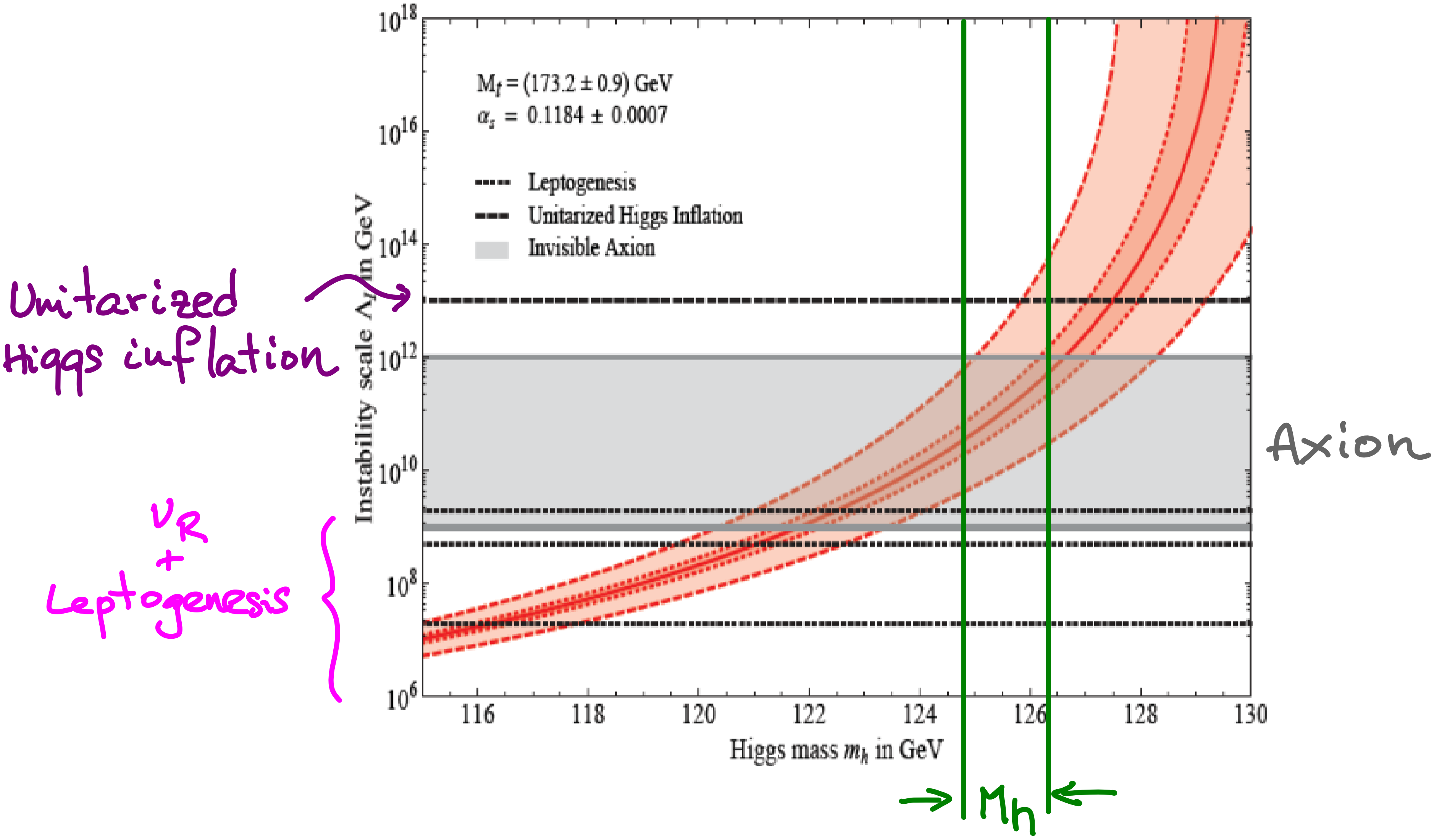
Is this compatible with leptogenesis constraints on M_N?



Different initial conditions ρ_{ν_R} density

2×10^9 GeV
5×10^8 GeV
2×10^7 GeV

SINGLET STABILIZATION IN MODELS



CONCLUSIONS

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

★ $M_h \simeq 125$ GeV ⇒ Unstable EW vacuum w/o BSM

Long-lived and intriguinly close to stability boundary

This instability has implications for

- Cosmology Reheating T, Higgs inflation
- BSM See-saw, etc

★ Singlet stabilization

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

It can be embedded in many scenarios, well motivated for other reasons.

But, let's hope for natural BSM @ LHC14!

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

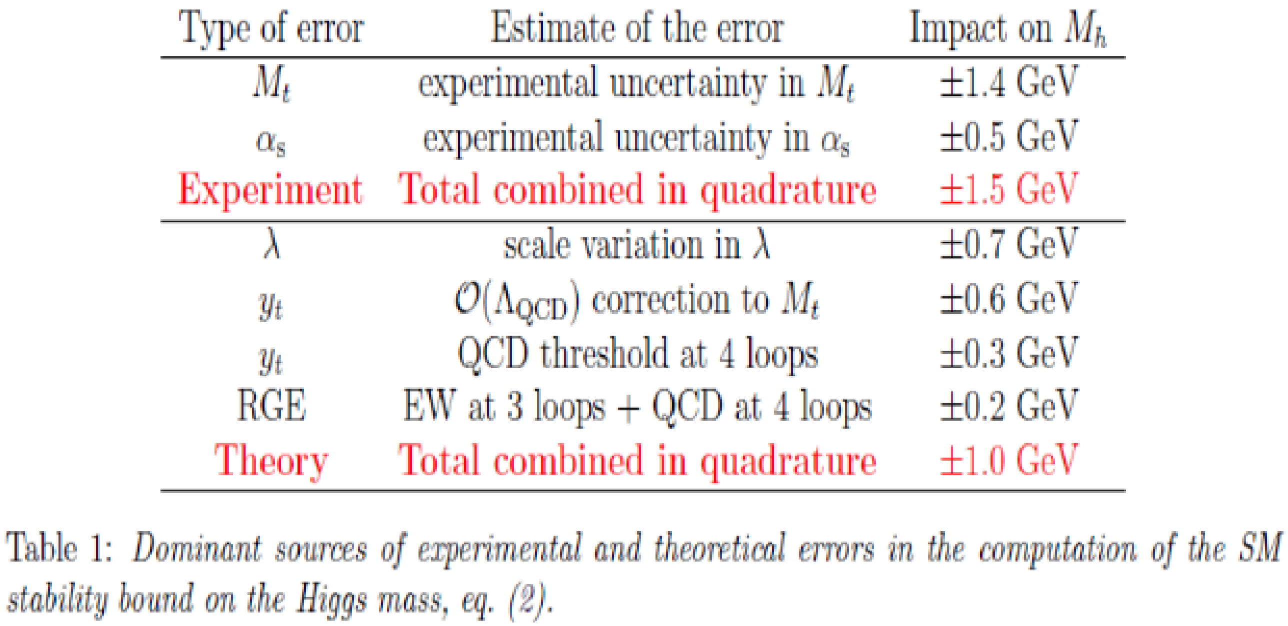
$$M_t = 173.3 \pm 2.8 \text{ GeV}$$

would still allow for stability

Alekhin, Djouadi, Moch'12

Too conservative given the good agreement...

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	$\mathcal{O}(\Lambda_{\rm QCD})$ 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).*

SM + SINGLET RGES

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