STABILITY OF THE EW VACUUM AFTER THE FIRST LHC RUN

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OUTLINE

- ★ Context: Status after first LHC run
  Higgs discovered, no trace of BSM...

- ★ $M_h \simeq 125$ GeV ⇨ EW vacuum unstable

- ★ Several implications of this instability

REFERENCES

EARLY WORK ON VACUUM INSTABILITY

I. Krive, A. Linde '76

N. Krasnikov '78

L. Maiani, G. Parisi, R. Petronzio '78 + N. Cabibbo '79

H. Politzer, S. Wolfram '79

P. Hung '79

A. Linde '80

M. Lindner '86 + M. Sher, H. Zaglauer '89

P. Arnold, S. Vokos '91 + ... many more

REFERENCES

RECENT PRECISION STUDIES

... +

M. Holthausen, K.S. Lim, M. Lindner [ph/1112.2415]

J. Elias-Miró, JRE, G.F. Giudice, G. Isidori, A. Riotto, A. Strumia [ph/1112.3022]

F. Bezrukov, M.Y. Kalmykov, B.A. Kniehl, M. Shaposhnikov [ph/1205.2893]

G. Degrassi, S. Di Vita, J. Elias-Miró, JRE, G.F. Giudice, G. Isidori, A. Strumia [ph/1205.6497]

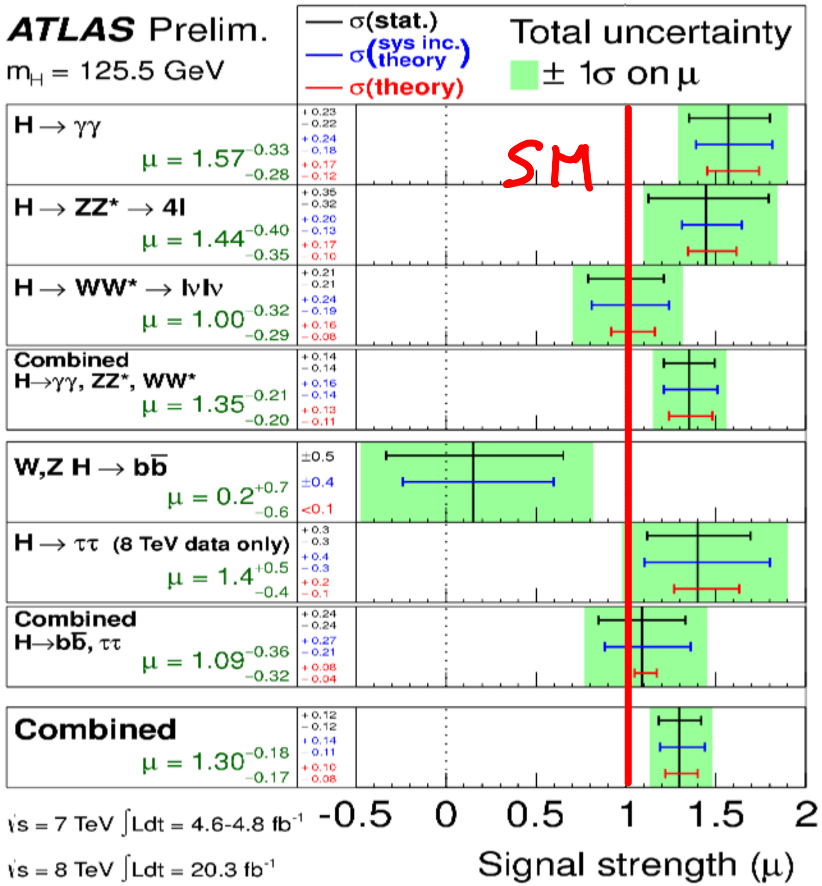
S. Alekhin, A. Djouadi, S. Moch [ph/1207.0980]

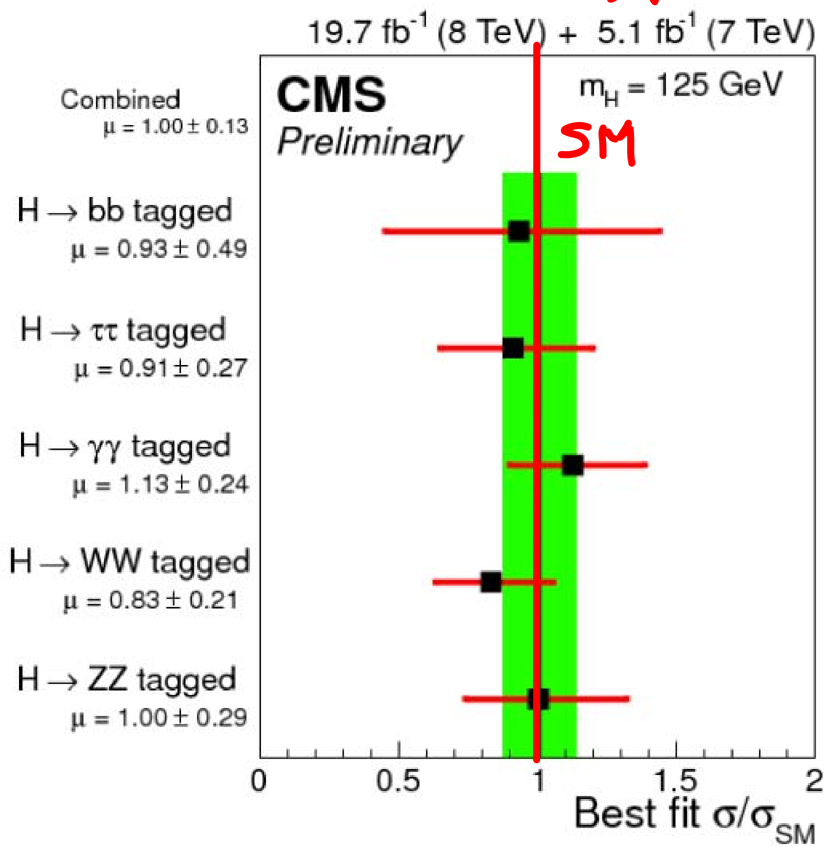
D. Buttazzo, G. Degrassi, P. Giardino, G. Giudice, F. Sala, A. Salvio, A. Strumia [ph/1307.3536]

SM STATUS

ICHEP'14

- Higgs discovered, close to SM-like





Mh/GeV = 125.36 + 0.37 (stat) + 0.18 (syst) ATLAS

Mh/GeV = 125.03 + 0.26/-0.27 (stat) + 0.13/-0.15 (syst) CMS

SM STATUS

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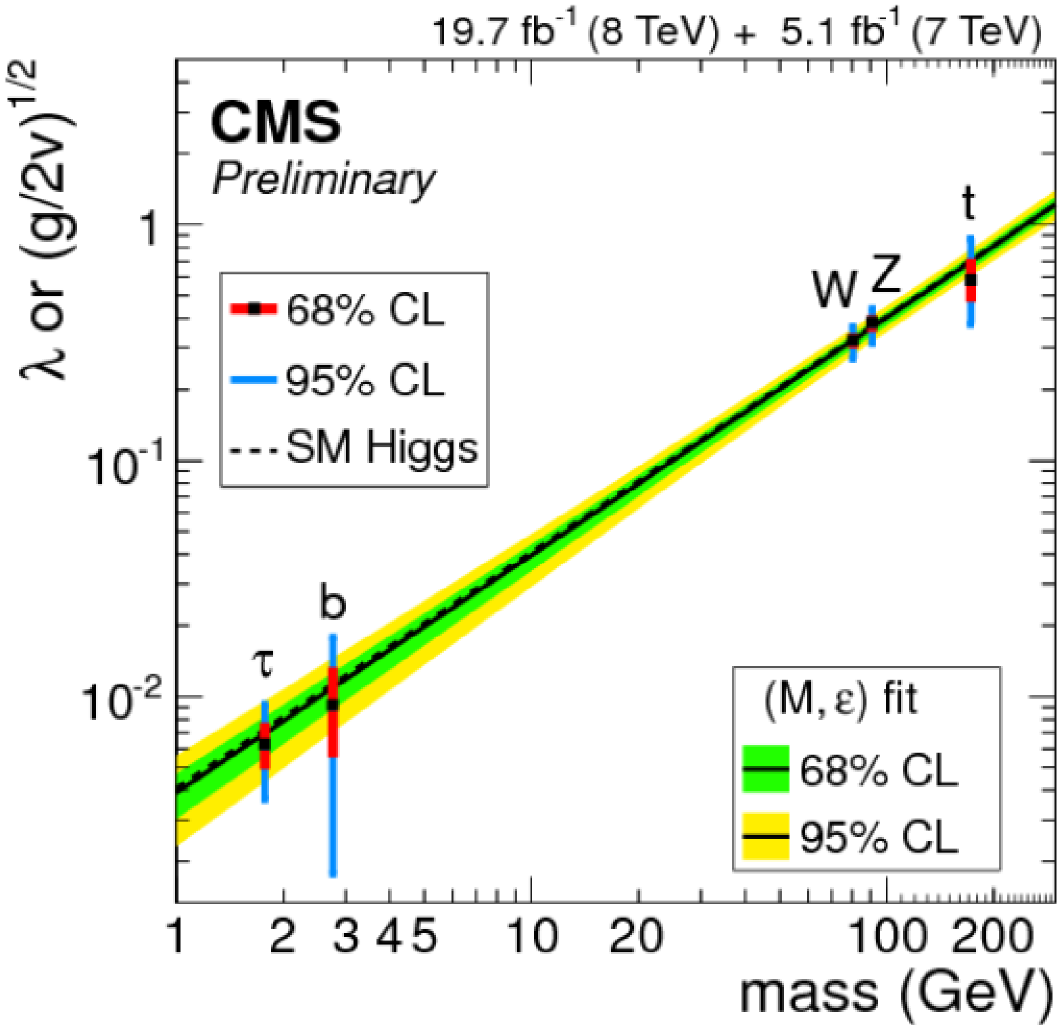
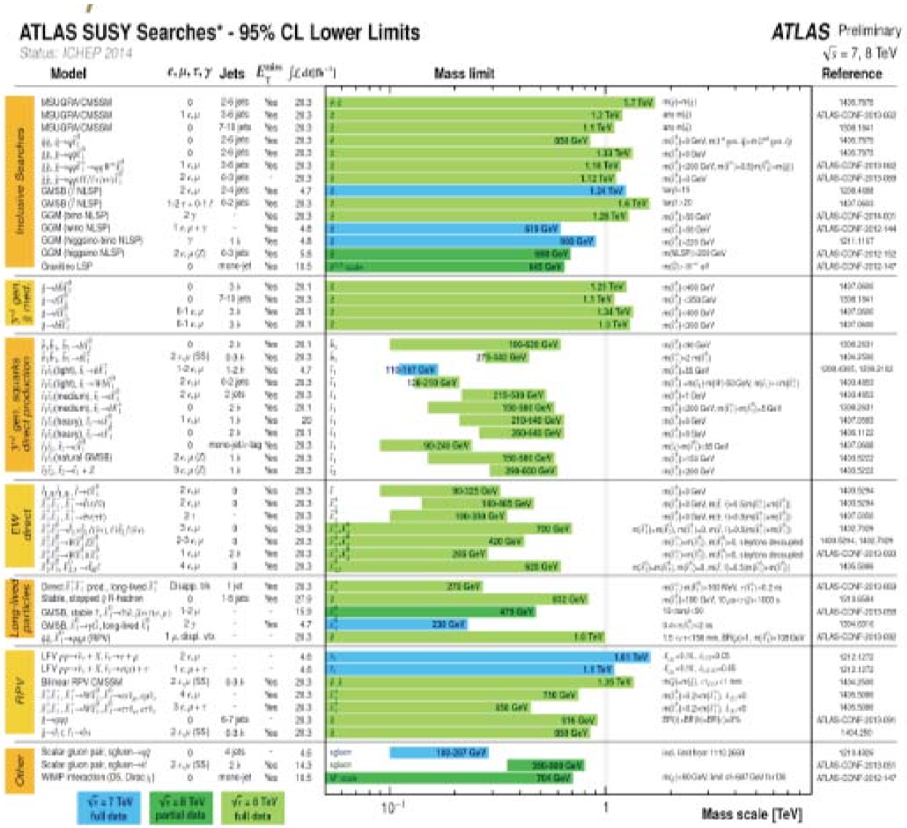


BSM STATUS

- No trace of BSM so far ⇨ $\Lambda >$ few TeV ?

"TSUNAMI" EXCLUSION PLOTS

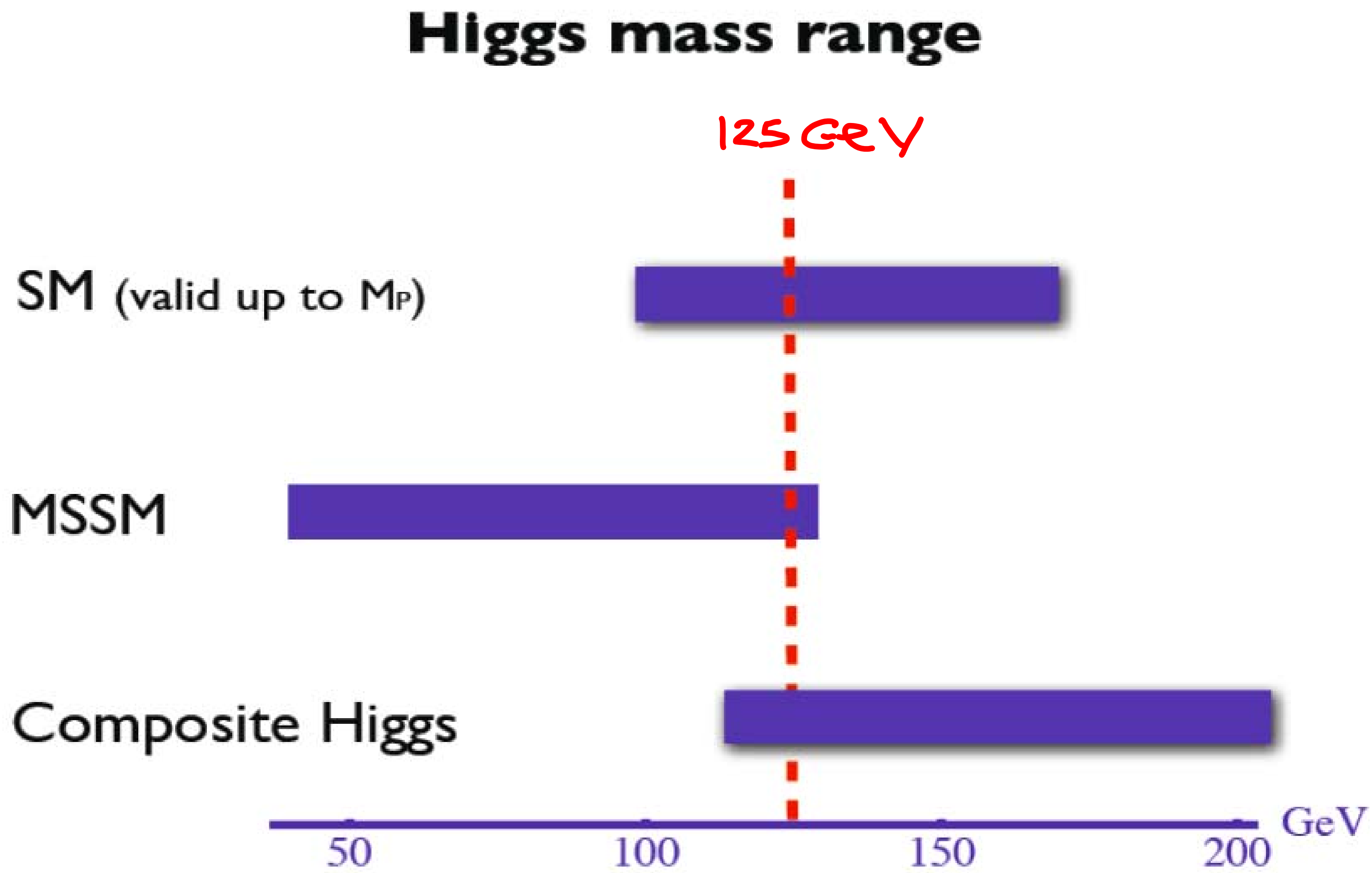
ICHEP'14



SUSY

EXOTICS

M_h AS MODEL DISCRIMINATOR



A. Pomarol, ICHEP'12

BSM STATUS

- Higgs discovered, close to SM-like

+

- No trace of BSM so far ⇒ $\Lambda >$ few TeV ?

+

- Holding on to naturalness

⇓

$\Lambda \sim$ few TeV

BSM STATUS / THIS TALK

- Higgs discovered, close to SM-like

+

- No trace of BSM so far ⇨ $\Lambda \gg$ few TeV ?

+

- Disregarding naturalness

⇩

$\Lambda \sim M_{Pl}$?

SM EXTRAPOLATION

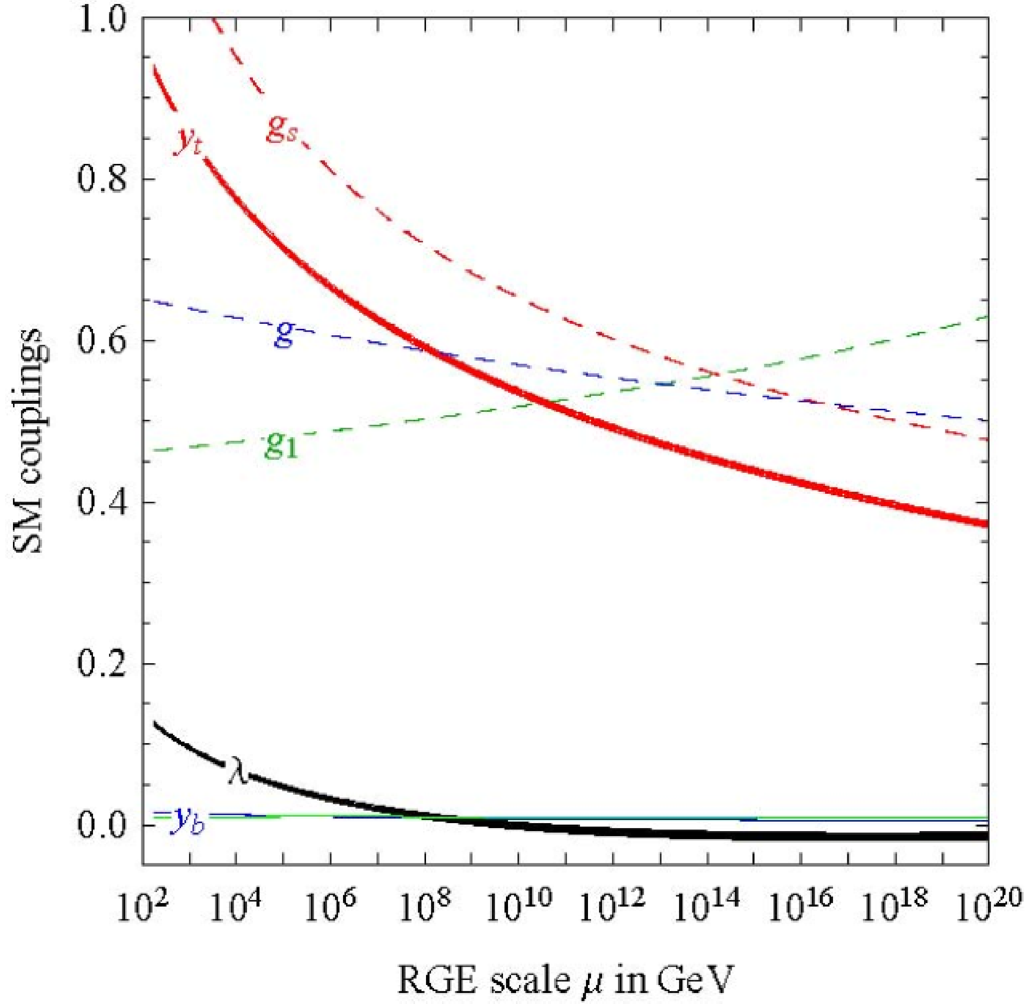
Assume Higgs has SM props. and no BSM Physics

All SM parameters known

$M_h \Rightarrow \lambda(EW)$

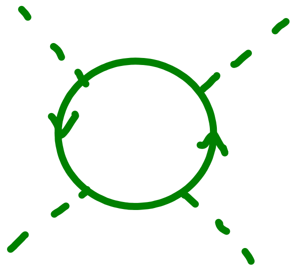
Forgetting naturalness, can the pure SM be valid up to M_{Pl}?

Weakly coupled up to M_{Pl}



VACUUM INSTABILITY

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

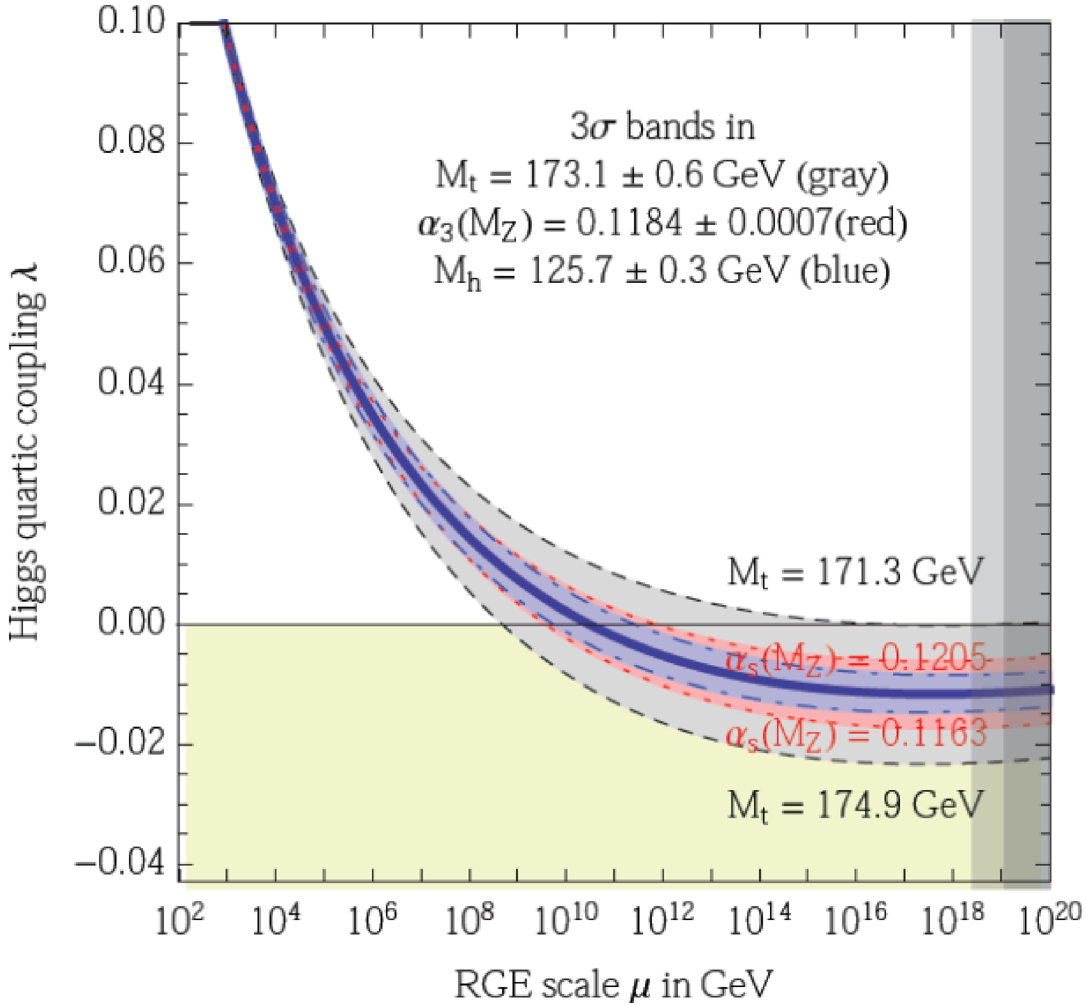


$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

⇓

Higgs potential instability

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



Buttazzo et al '13

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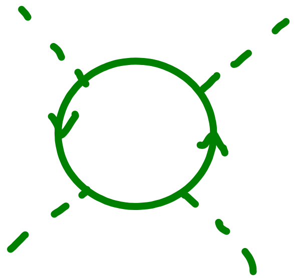

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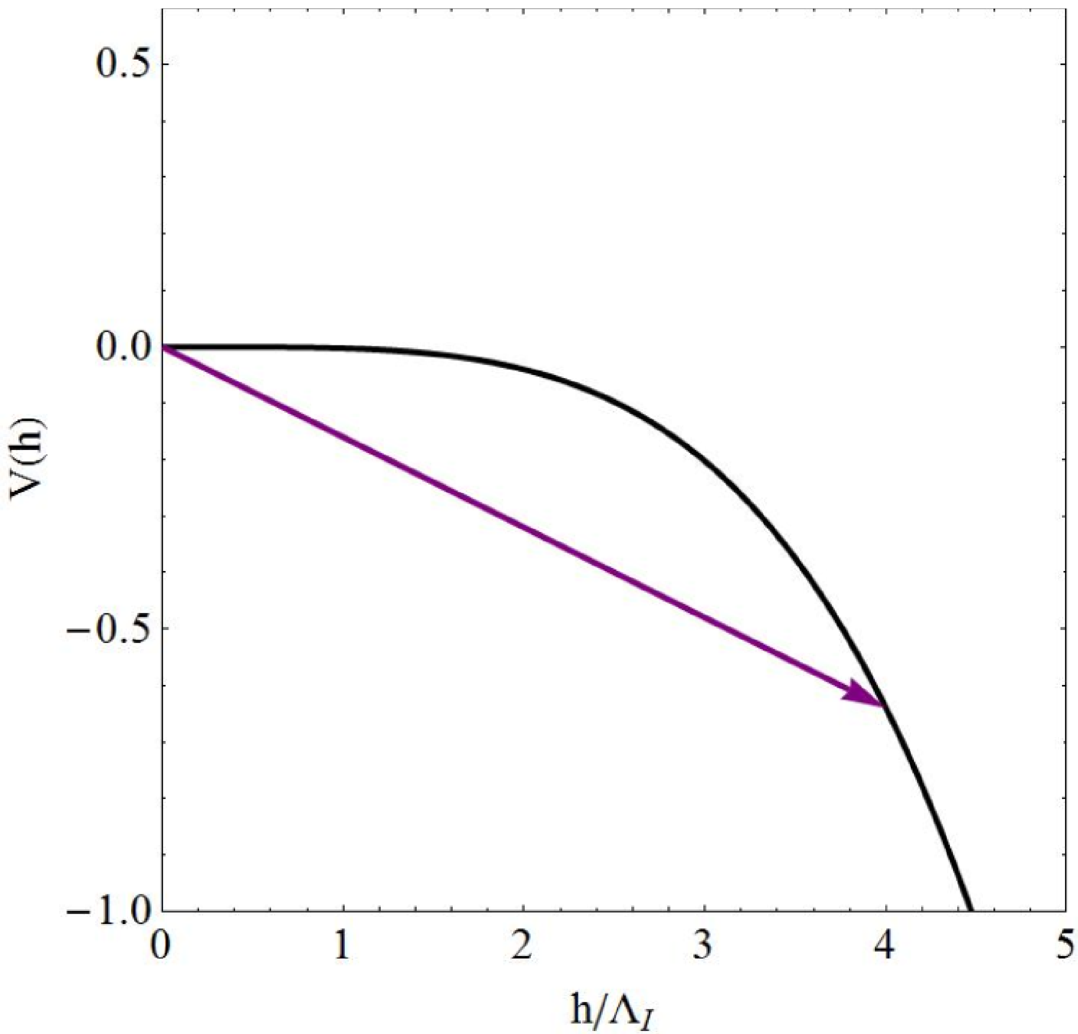

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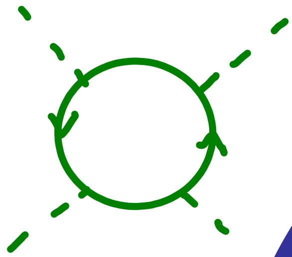

$\lambda < 0$ at $\Lambda_I \sim 10^{10}$ GeV

$\Downarrow$

Higgs potential instability

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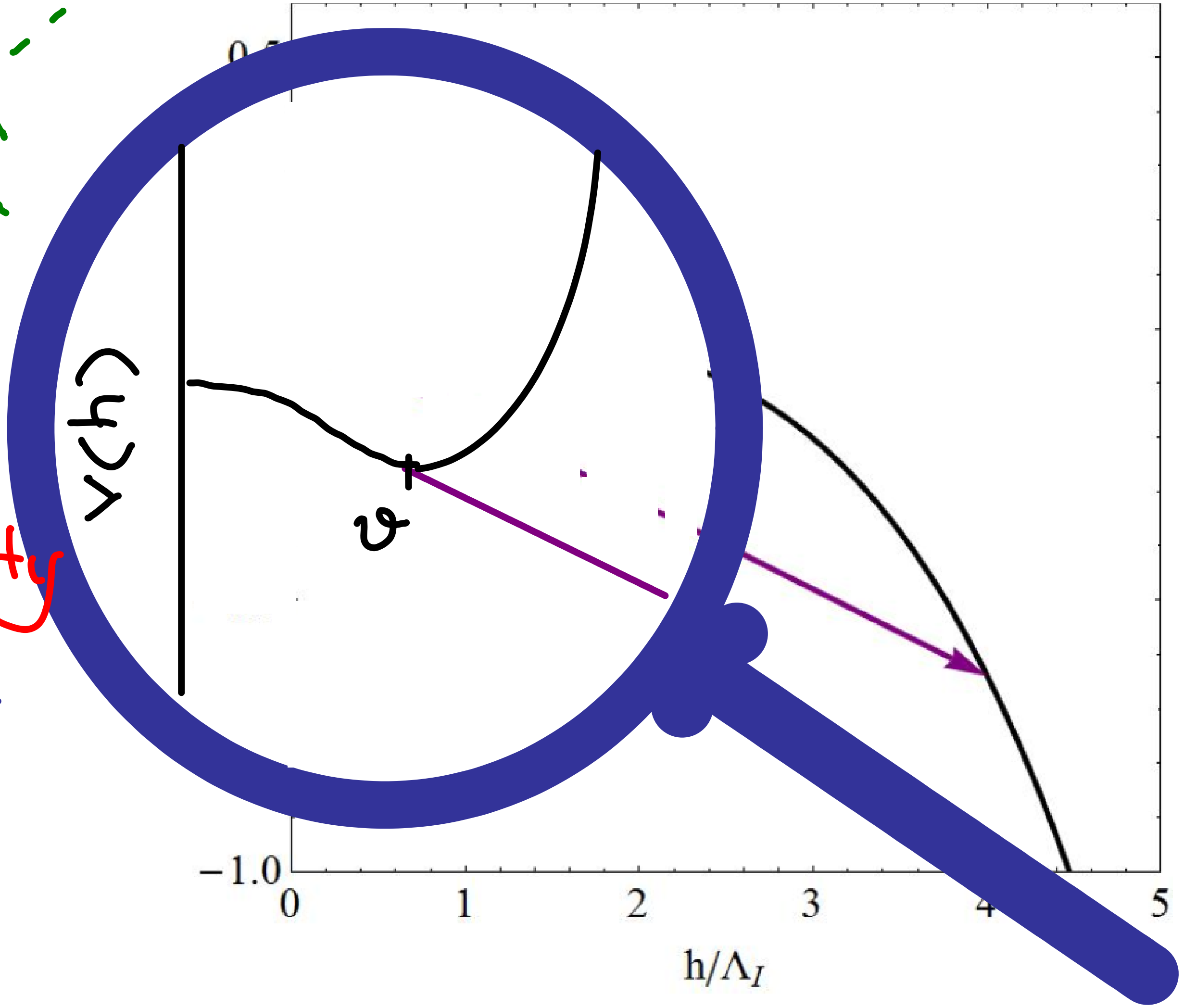


LIFE IN A METASTABLE VACUUM

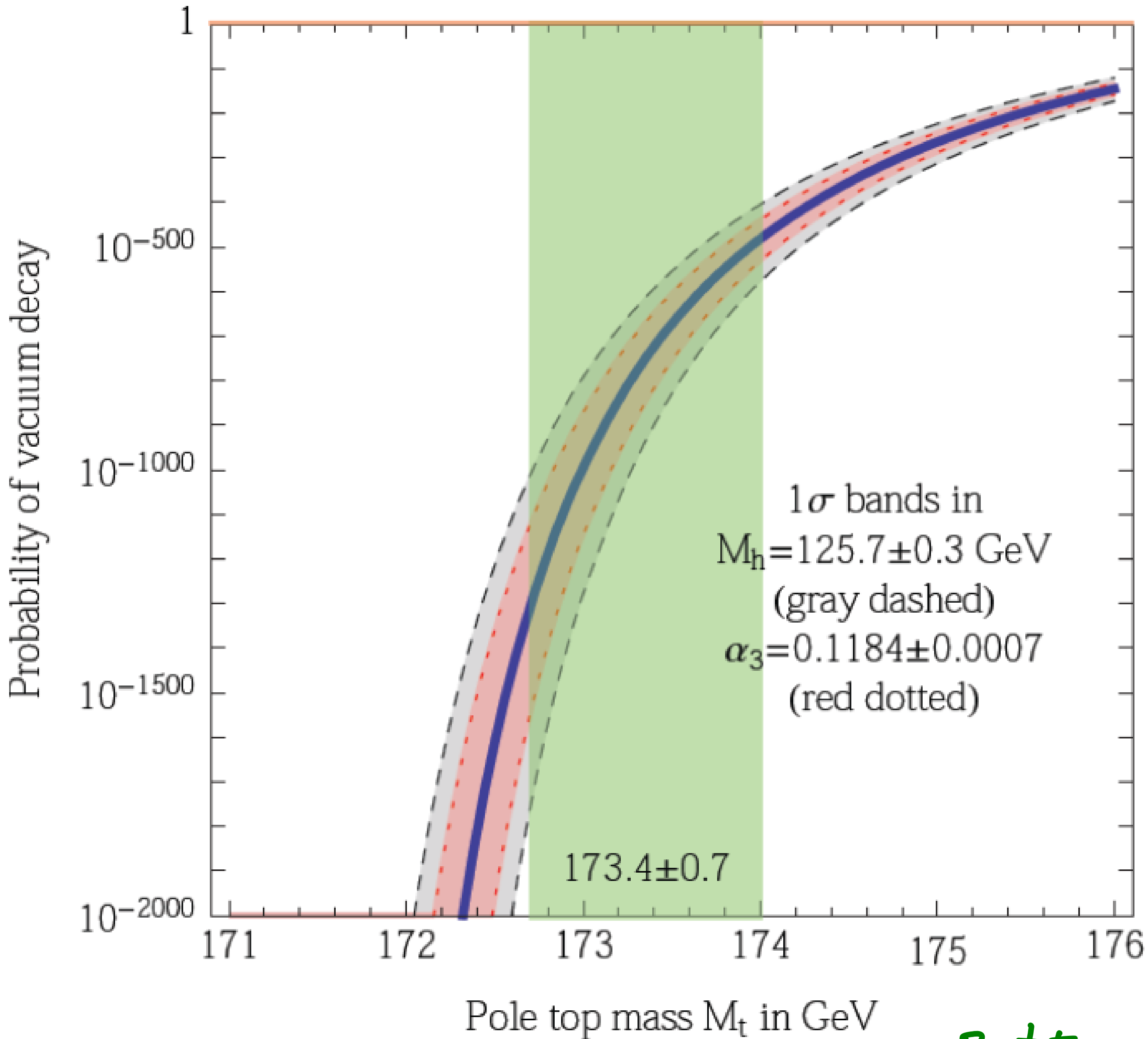
$$p = \text{Decay prob.} = \underbrace{\frac{\text{Decay rate}}{\Delta t \cdot \Delta V}}_{h^4 e^{-S_4}} \tau_U^4 \quad \text{with } \tau_U^4 \sim \left(e^{140}/M_{Pl}\right)^4$$

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

easily wins over τ_U^4

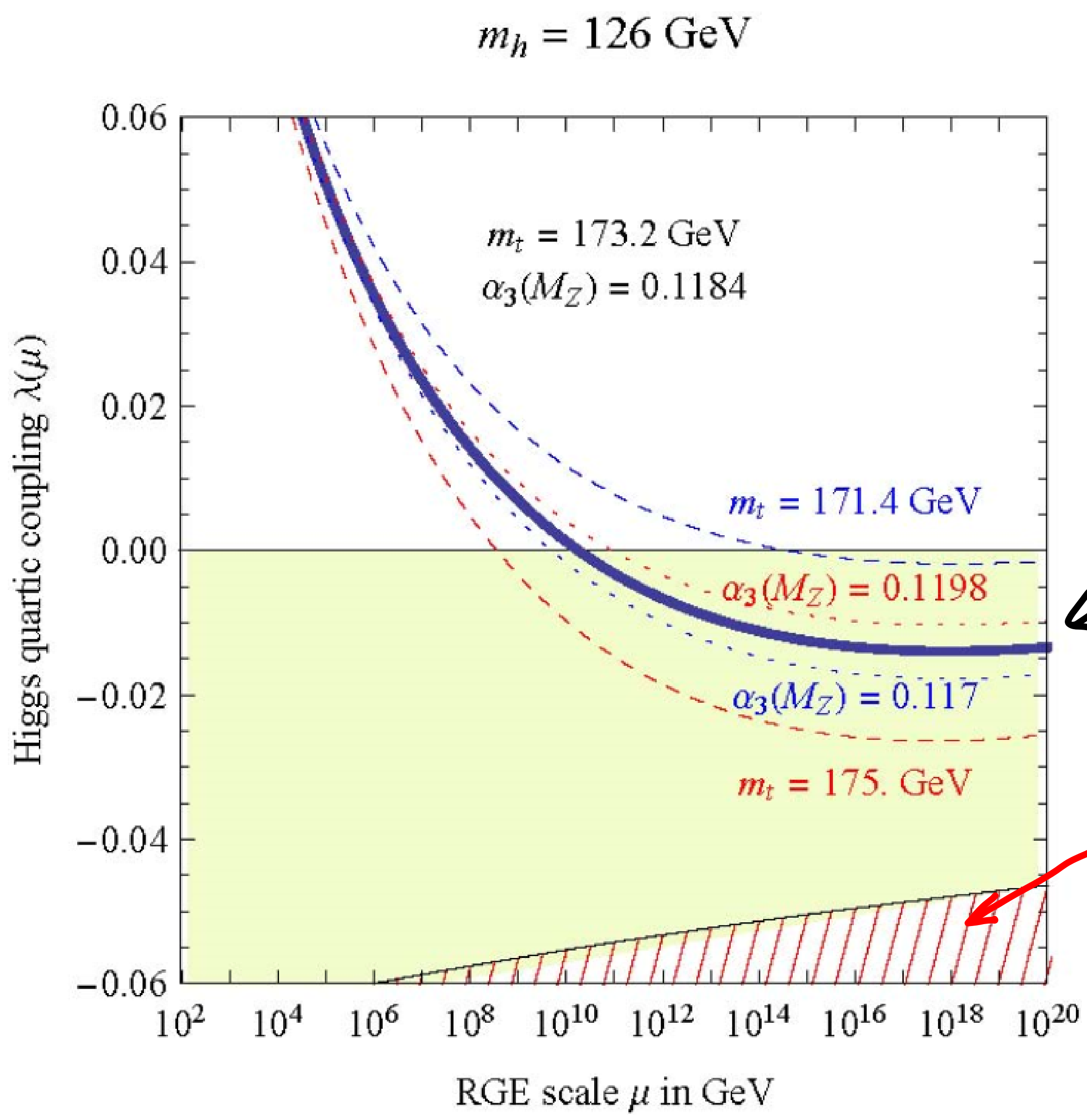
$p \lll 1$: Lifetime of EW vacuum much longer than τ_U

PROBABILITY OF VACUUM DECAY



Buttazzo et al '13

LIFE IN A METASTABLE VACUUM



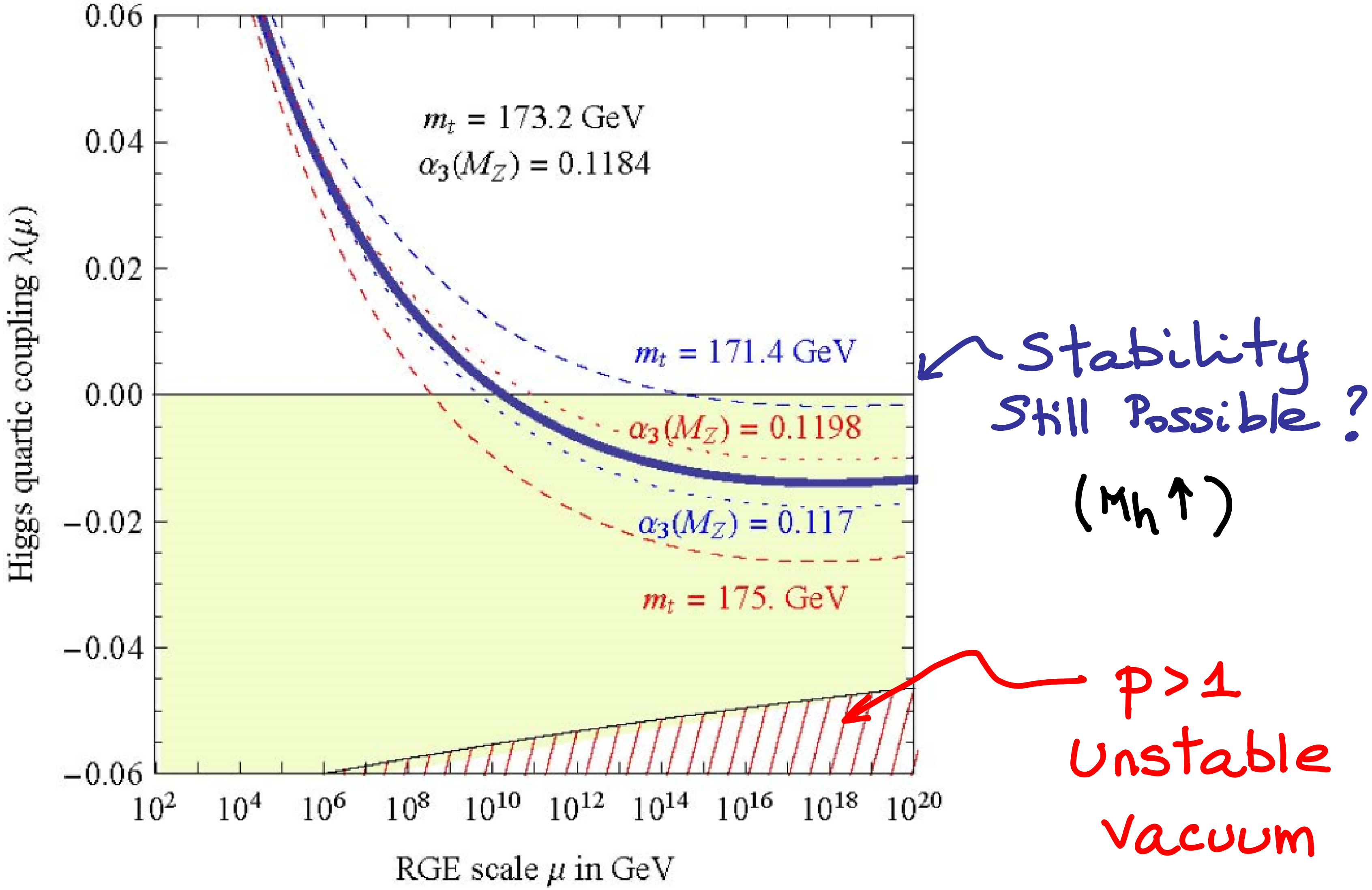
Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

$P > 1$
Unstable vacuum
($M_h \downarrow$)

LIFE IN A METASTABLE VACUUM

$m_h = 126$ GeV



NNLO STABILITY BOUND

Lower bound on M_h for stability up to M_{Pl} :

State-of-the-art NNLO calculation:

- 2-loop V_{eff} (Ford, Jack, Jones [ph/0111190])

- 3-loop RGES (..., Chetyrkin, Zoller [ph/1205.2892], Bednyakov, Pikelner, Velizhanin [ph/1212.6829])

- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$
(..., Shaposhnikov et al [ph/1205.2893], , Degrassi et al [ph/1205.6497], , Buttazzo et al [ph/1307.3536])

NNLO STABILITY BOUND

For stability up to M_{Pl} :

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

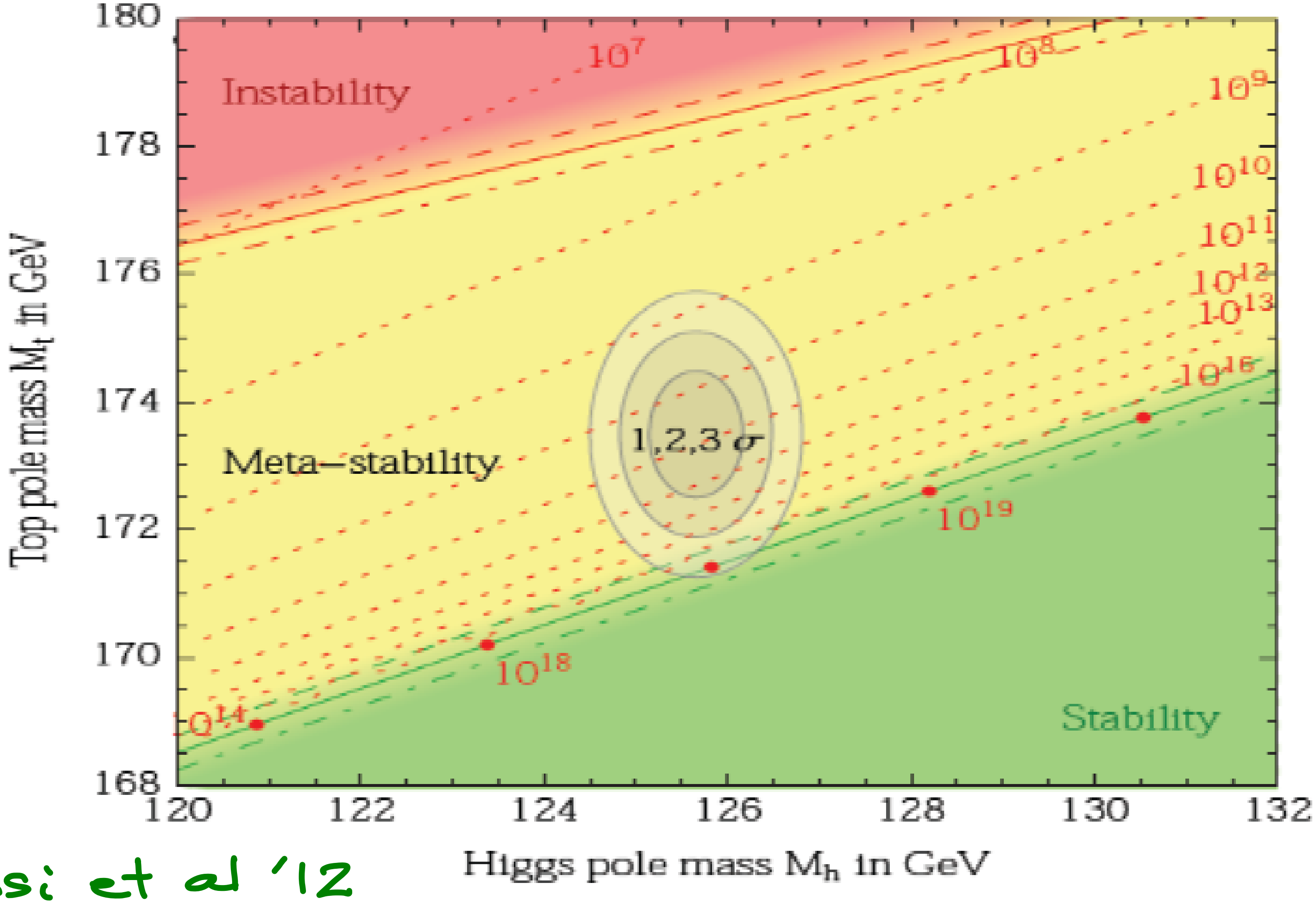
Degrassi et al '12

$$M_h\,[\mathrm{GeV}] > 129.6 + 2\left(\frac{M_t\,(\mathrm{GeV}) - 173.35}{1}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{th}$$

Buttazzo et al '13

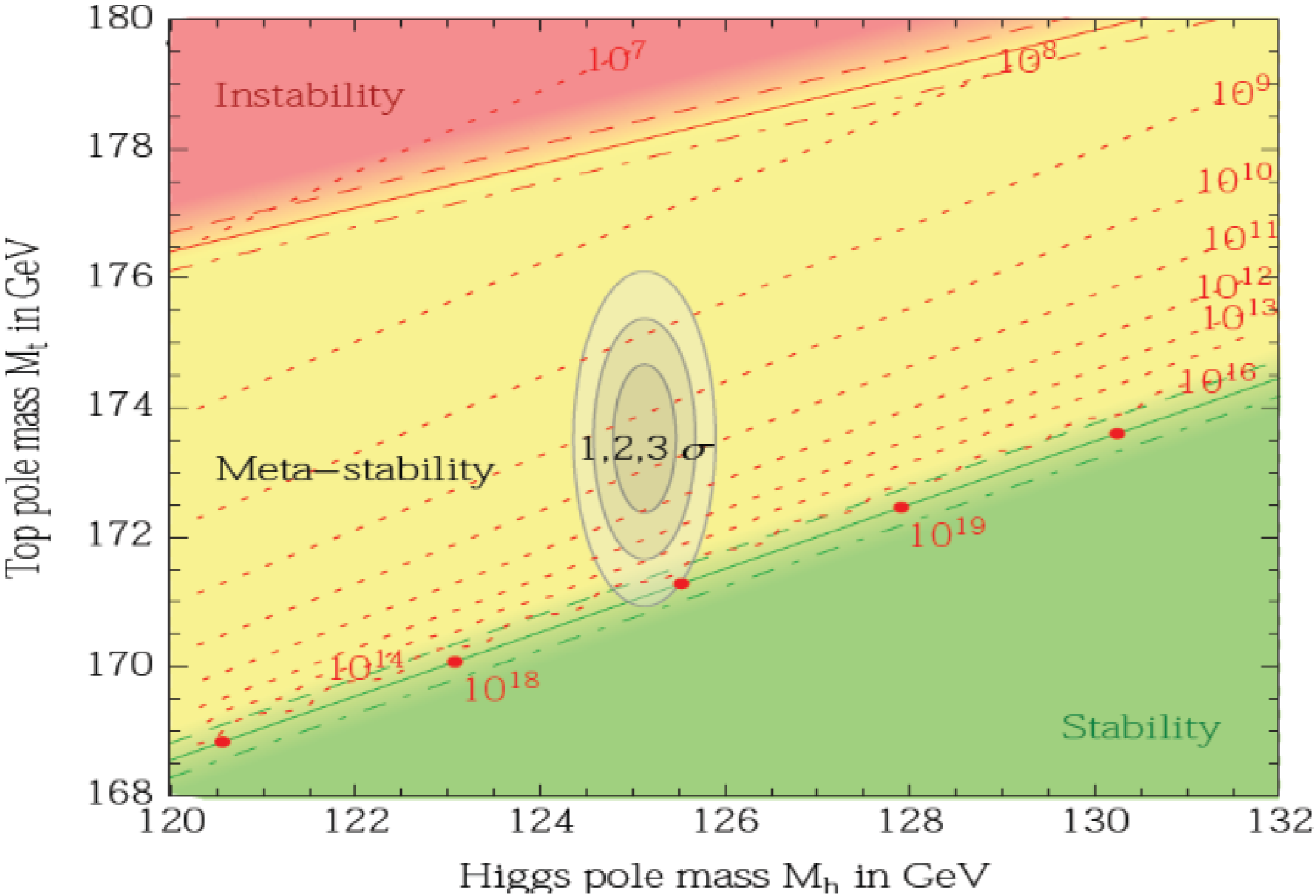
Both reduced previous theory error by a factor 3

LIVING AT THE EDGE



Degrassi et al '12
Buttazzo et al '13

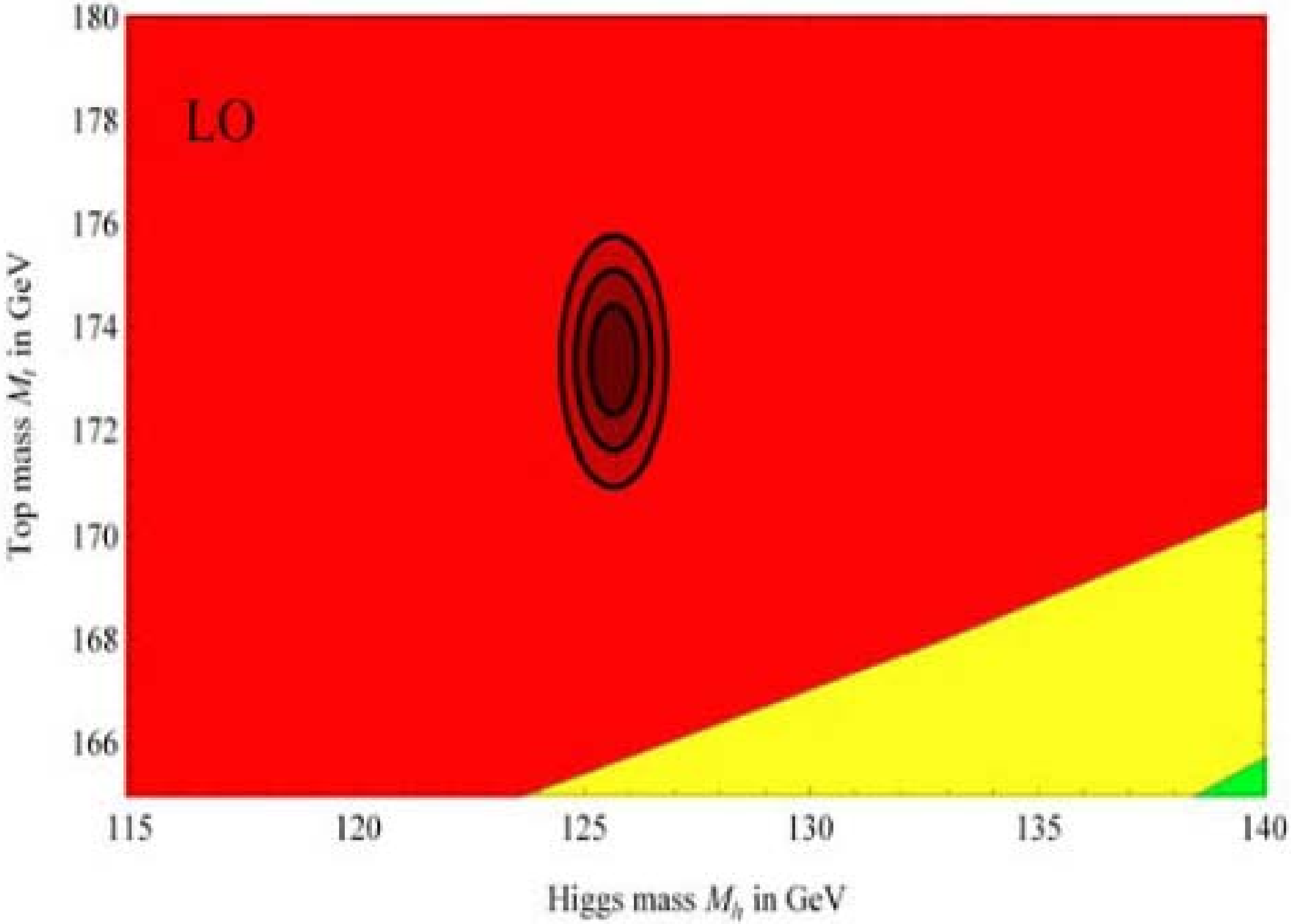
LIVING AT THE EDGE



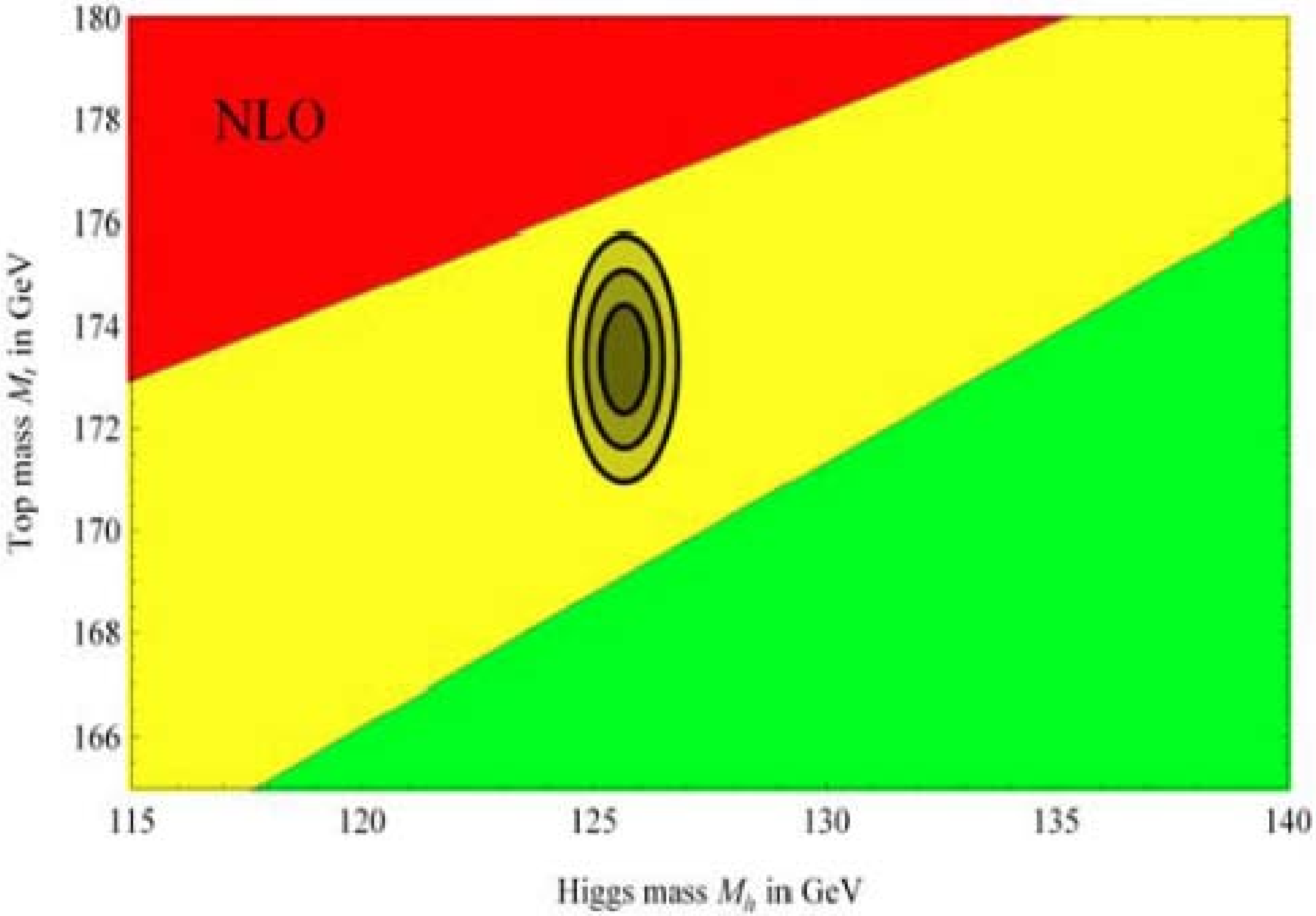
Update. $M_h = 125.13 \pm 0.23$ GeV $M_t = 173.34 \pm 0.76$ GeV

(thanks to A. Strumia)

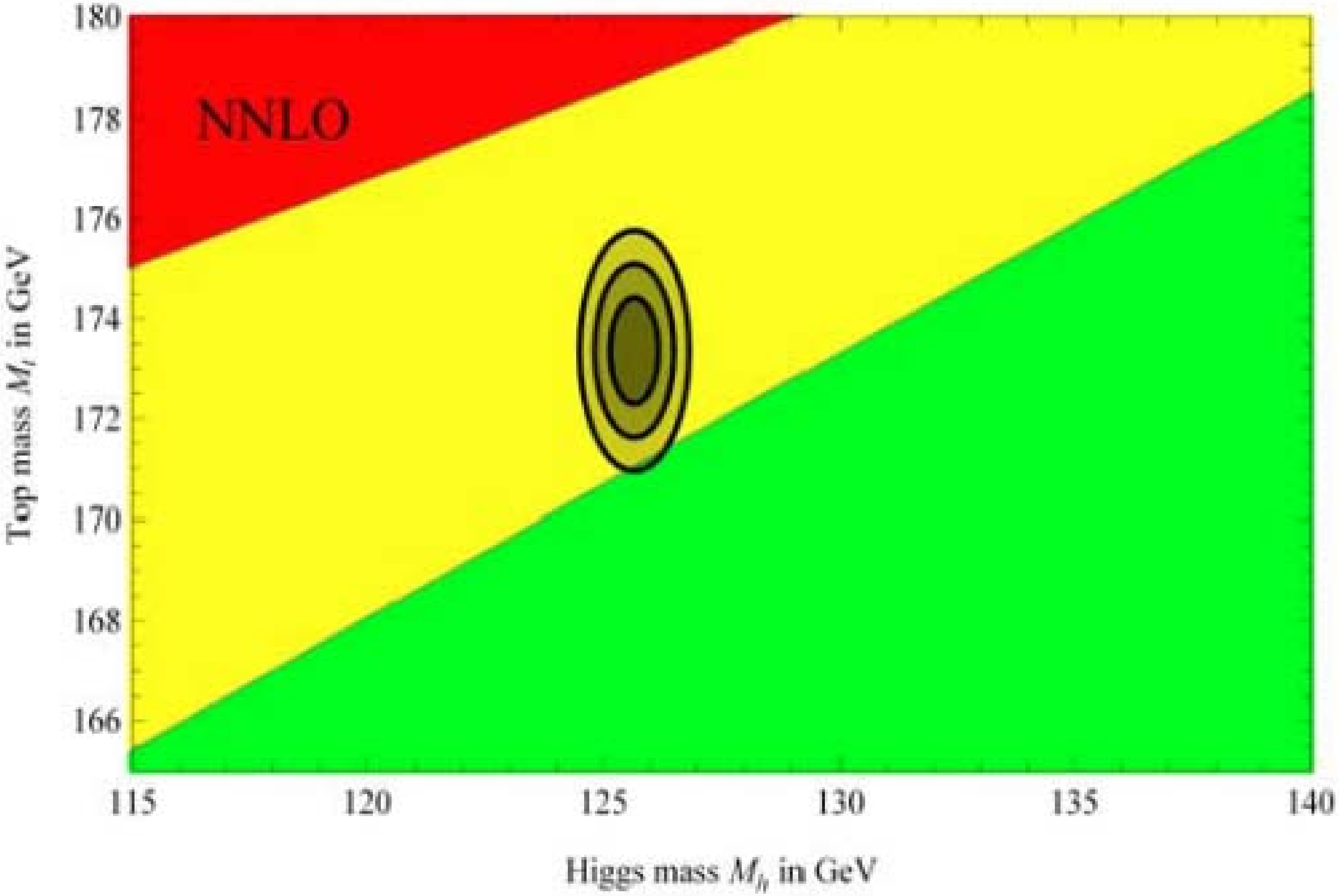
PROGRESS IN STABILITY CALCULATION



PROGRESS IN STABILITY CALCULATION



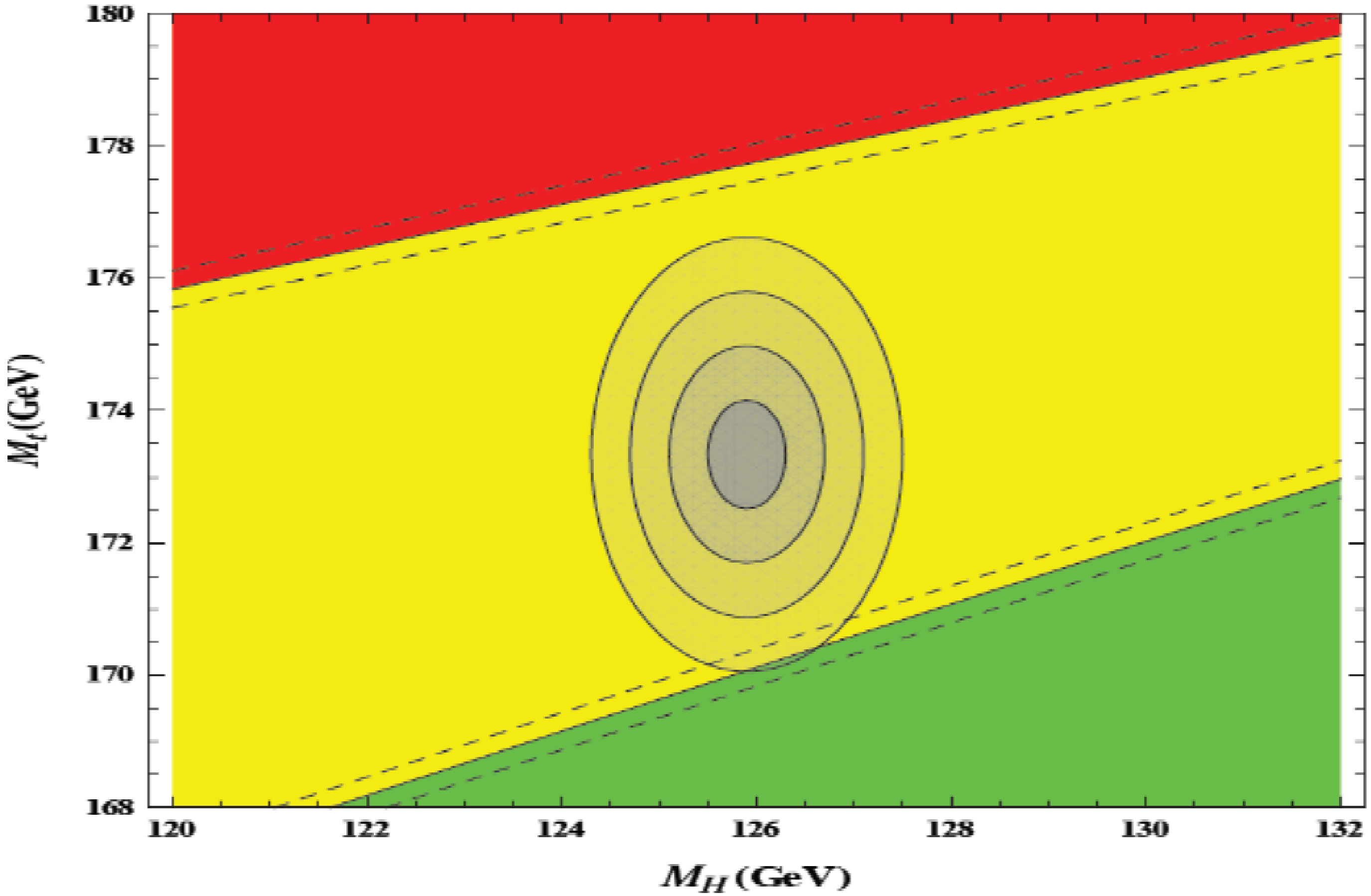
PROGRESS IN STABILITY CALCULATION



LIVING AT THE EDGE

Spencer-Smith, 1405.1975 Mass-dep. ren. scheme

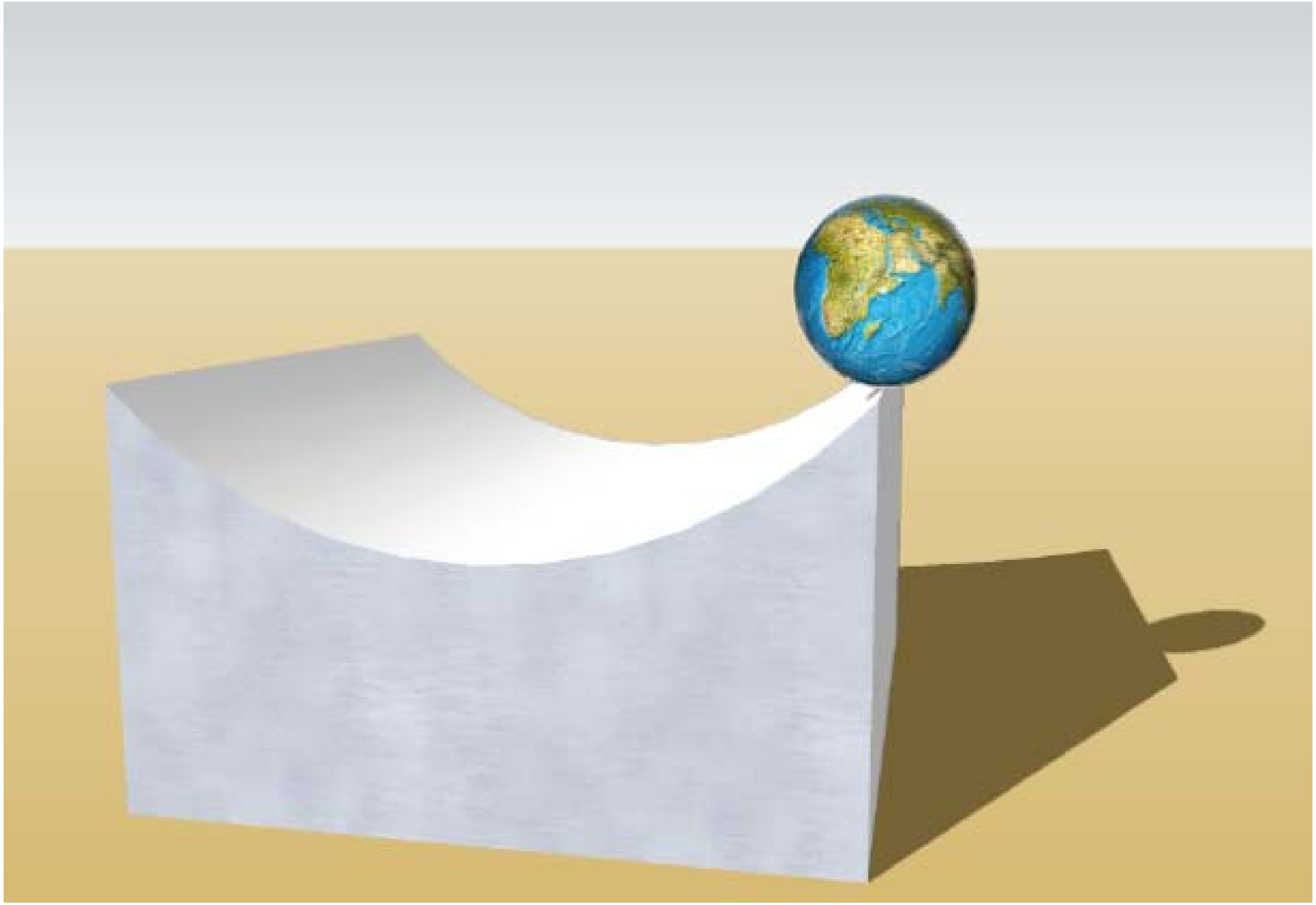
Stronger instability & Reduced errors



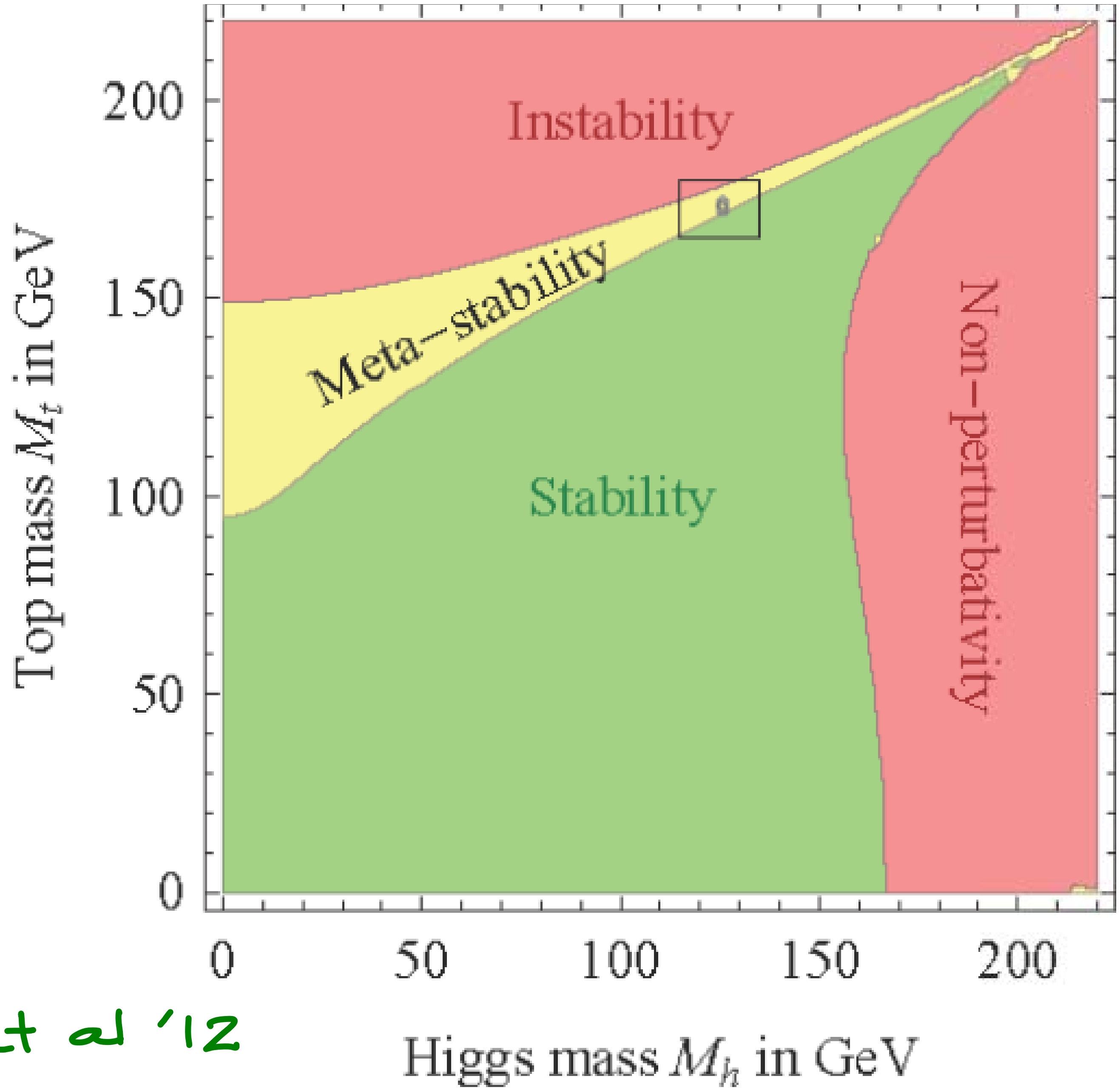
Stability disfavoured at ~3.5σ

Self-consistency ??

LIVING AT THE EDGE

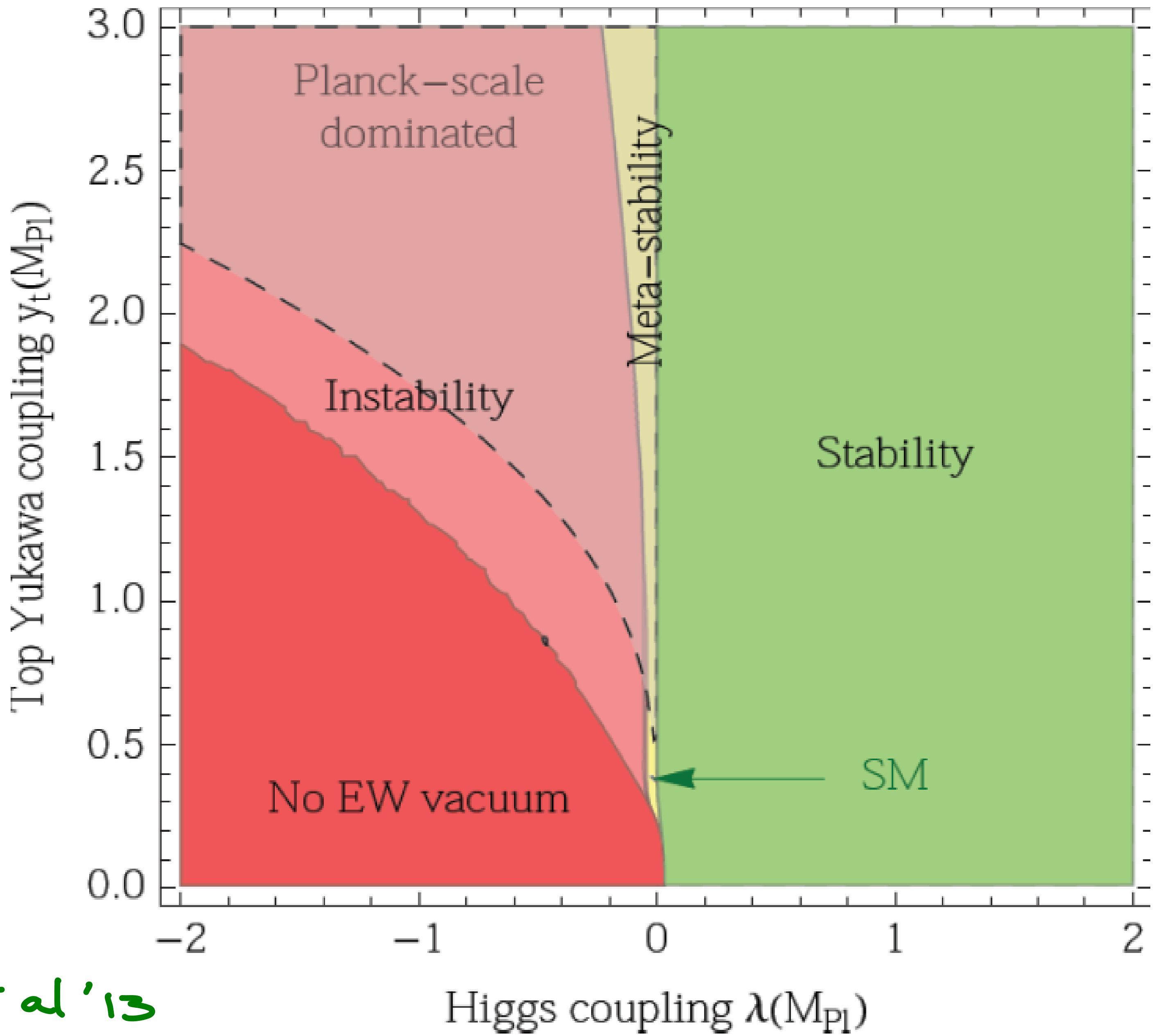


LIVING AT THE EDGE



Degrassi et al '12

LIVING AT THE EDGE



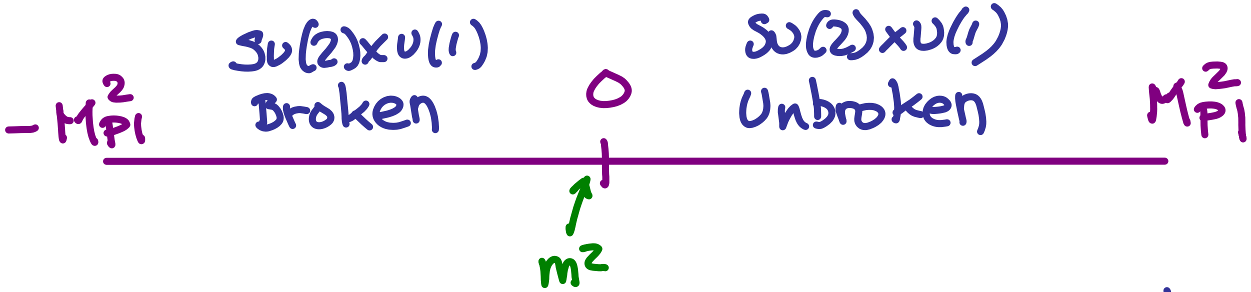
Buttazzo et al '13

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...

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

IRRELEVANT

MAKE IT WORSE

CURE IT

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

<u>Example</u>

<u>IRRELEVANT</u>

See-saw neutrinos

<u>MAKE IT WORSE</u>

<u>CURE IT</u>

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

<u>Example</u>

<u>IRRELEVANT</u> See-saw neutrinos

<u>MAKE IT WORSE</u> See-saw neutrinos

<u>CURE IT</u>

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

	Example
IRRELEVANT	See-saw neutrinos
MAKE IT WORSE	See-saw neutrinos
CURE IT	See-saw neutrinos (& SUSY!)

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

	Example
IRRELEVANT	See-saw neutrinos $M_R \lesssim 10^{13}$ GeV
MAKE IT WORSE	See-saw neutrinos $M_R \gtrsim 10^{13}$ GeV
CURE IT	See-saw neutrinos $M_R \sim \langle S \rangle$ & $\lambda_{HS} \lvert H \rvert^2 \lvert S \rvert^2$

Lebedev '12, Elias-Miro et al. '12

OTHER IMPLICATIONS

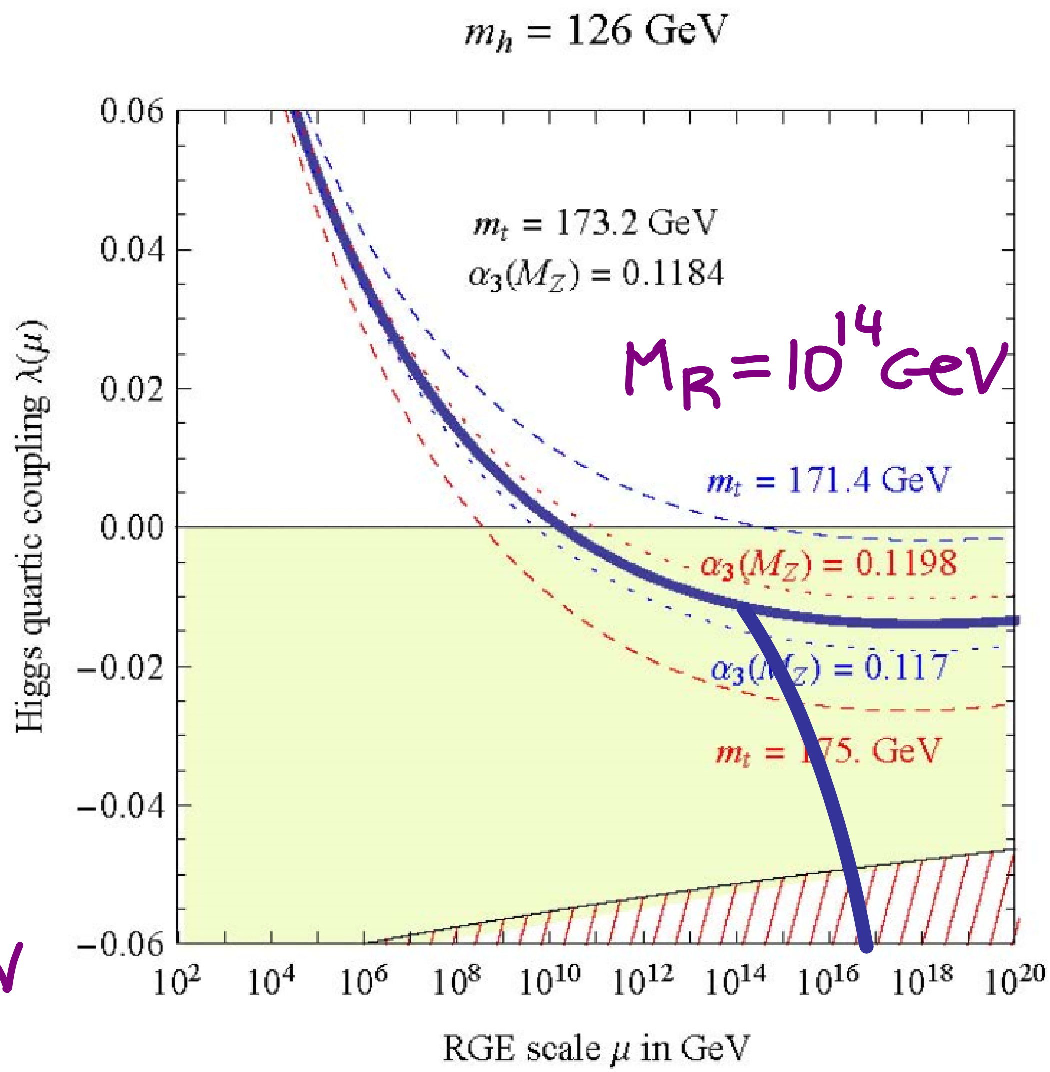
- See-saw neutrinos: Impact on $\beta_\lambda \supset -y_\nu^4/(16\pi^2)$ *

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

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

Adds to the top destabilizing effect

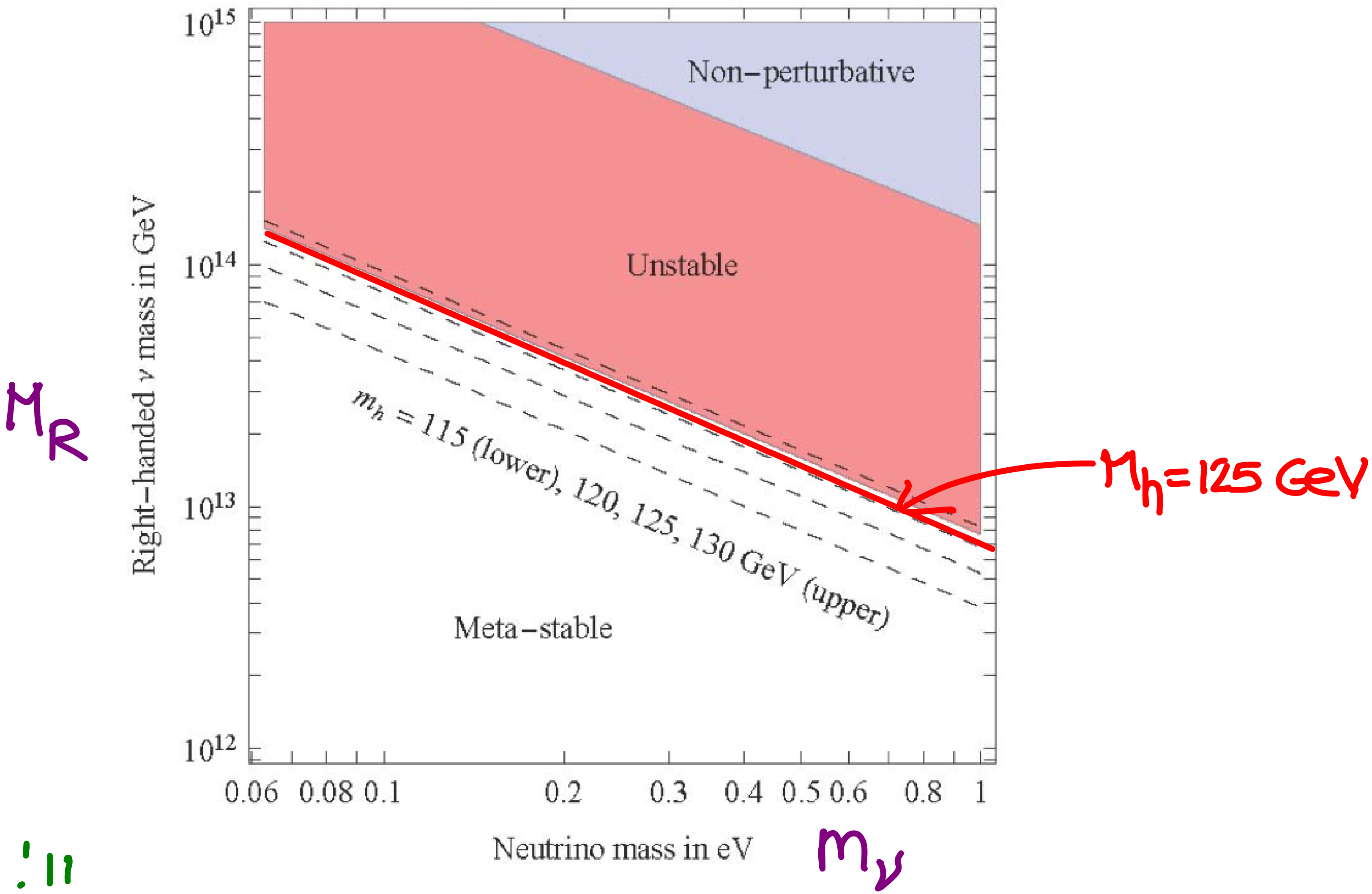
Important for $M_R \gtrsim 10^{13-14}$ GeV



Elias-Miro et al. '11

OTHER IMPLICATIONS

- See-saw neutrinos: Bound on M_{ν_R}



Elias-Miro et al '11

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 $w \gg v$)

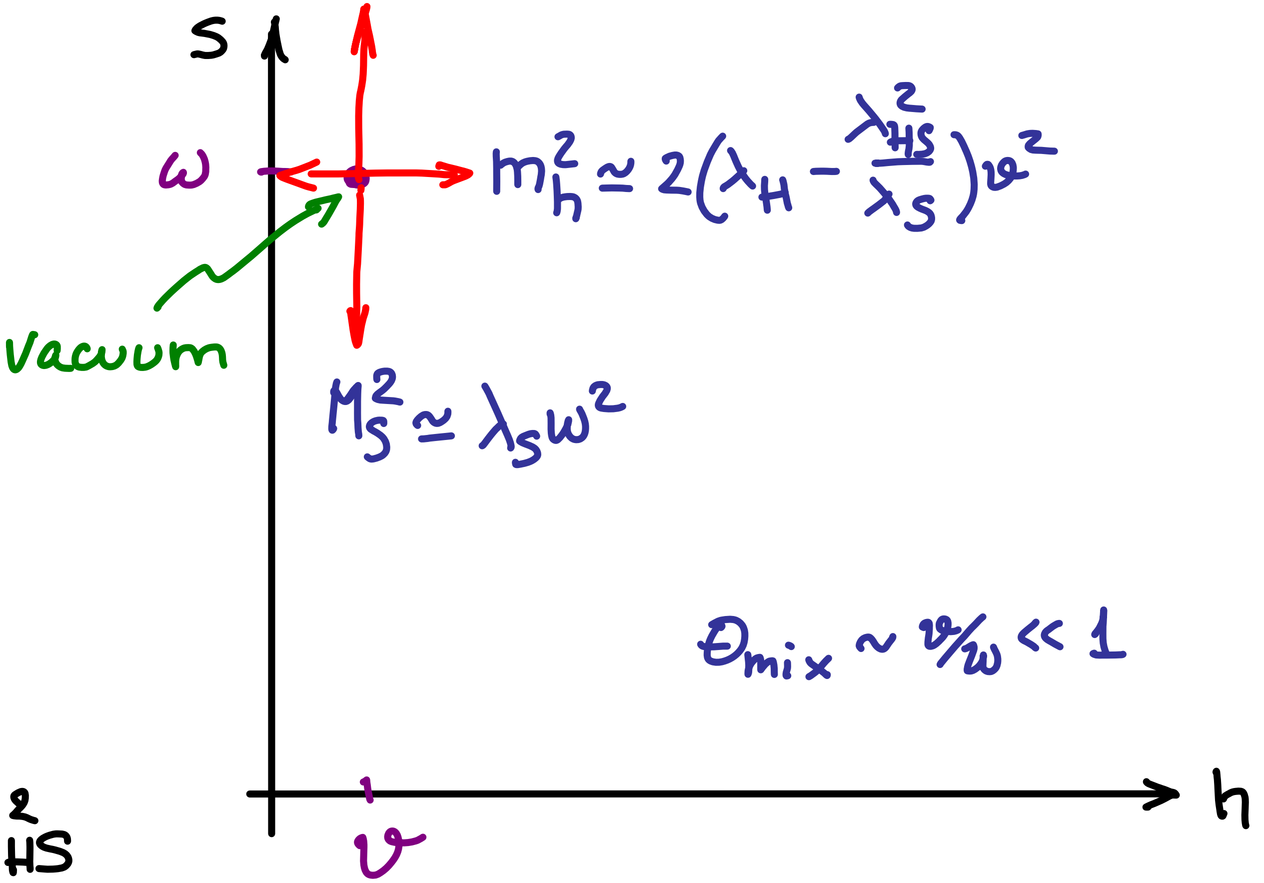
MODEL STRUCTURE

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:

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



$$\theta_{mix} \sim v/w \ll 1$$

LOW-ENERGY THEORY

Integrating out S $\Rightarrow$ Below M_S : SM

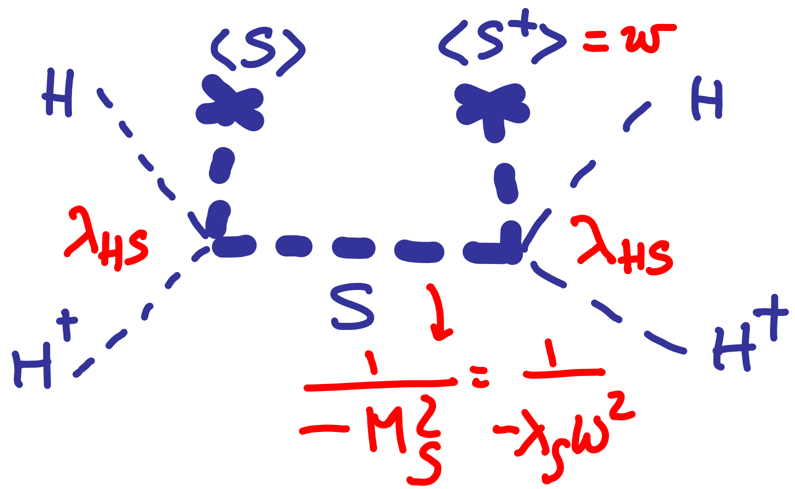
$$V(h) = \lambda \left(|H|^2 - v^2/2 \right)^2$$

$$\lambda \downarrow \quad \lambda_H - \frac{\lambda_{HS}^2}{\lambda_S}$$

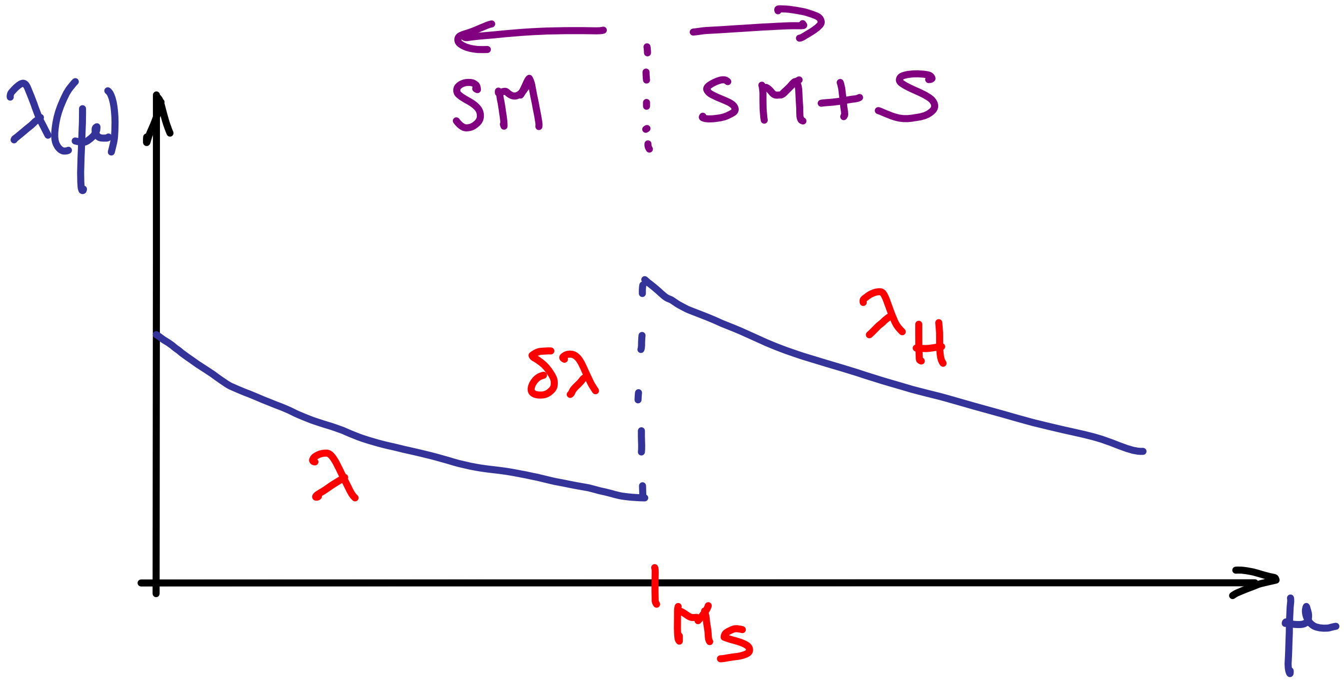
λ_H: original h quartic

$\frac{\lambda_{HS}^2}{\lambda_S}$: tree-level threshold correction

Diagrammatically



CRUCIAL THRESHOLD CORRECTION

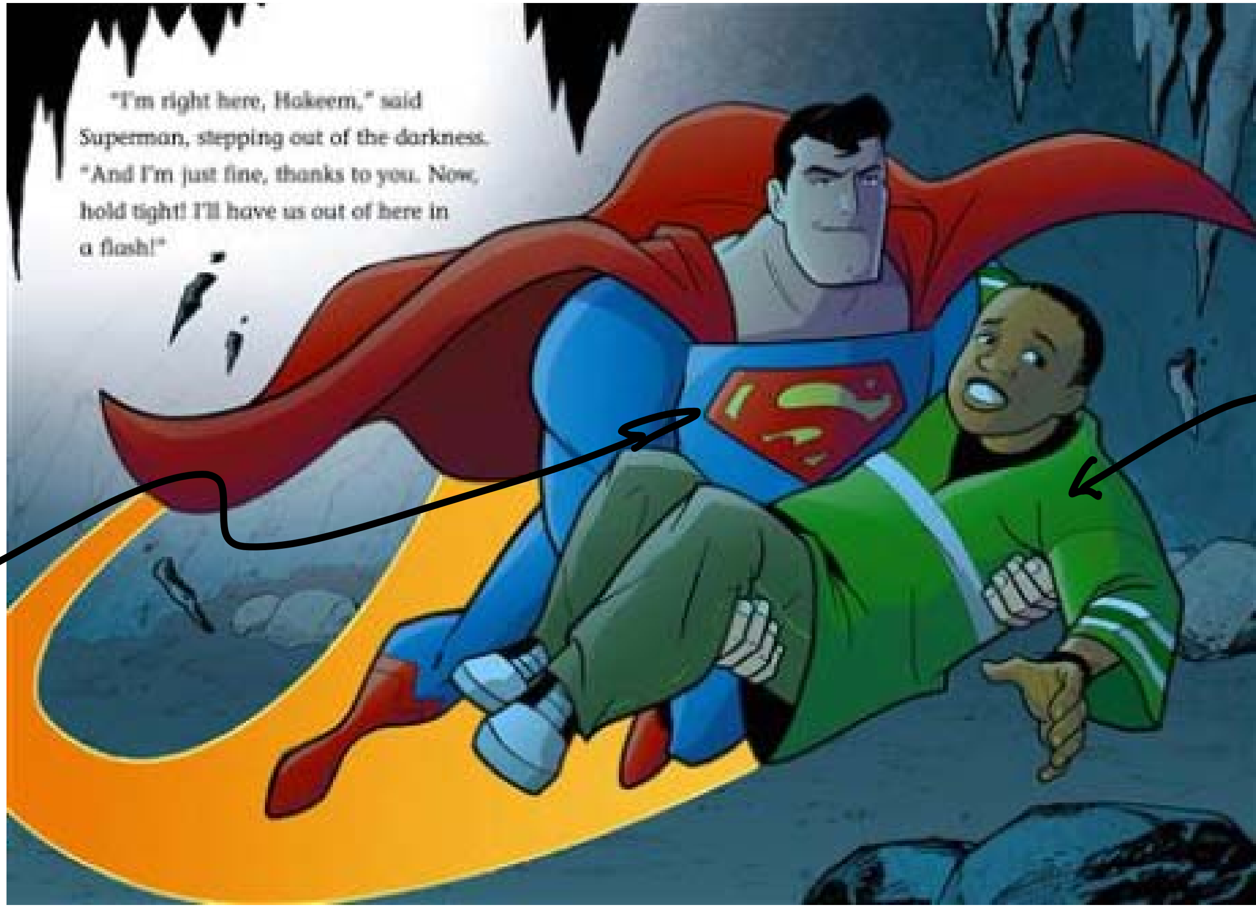


Matching at M_S : $\lambda(M_S) = \lambda_H(M_S) - \delta\lambda$

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

But, we must look more closely to stab. conditions

CRUCIAL THRESHOLD CORRECTION



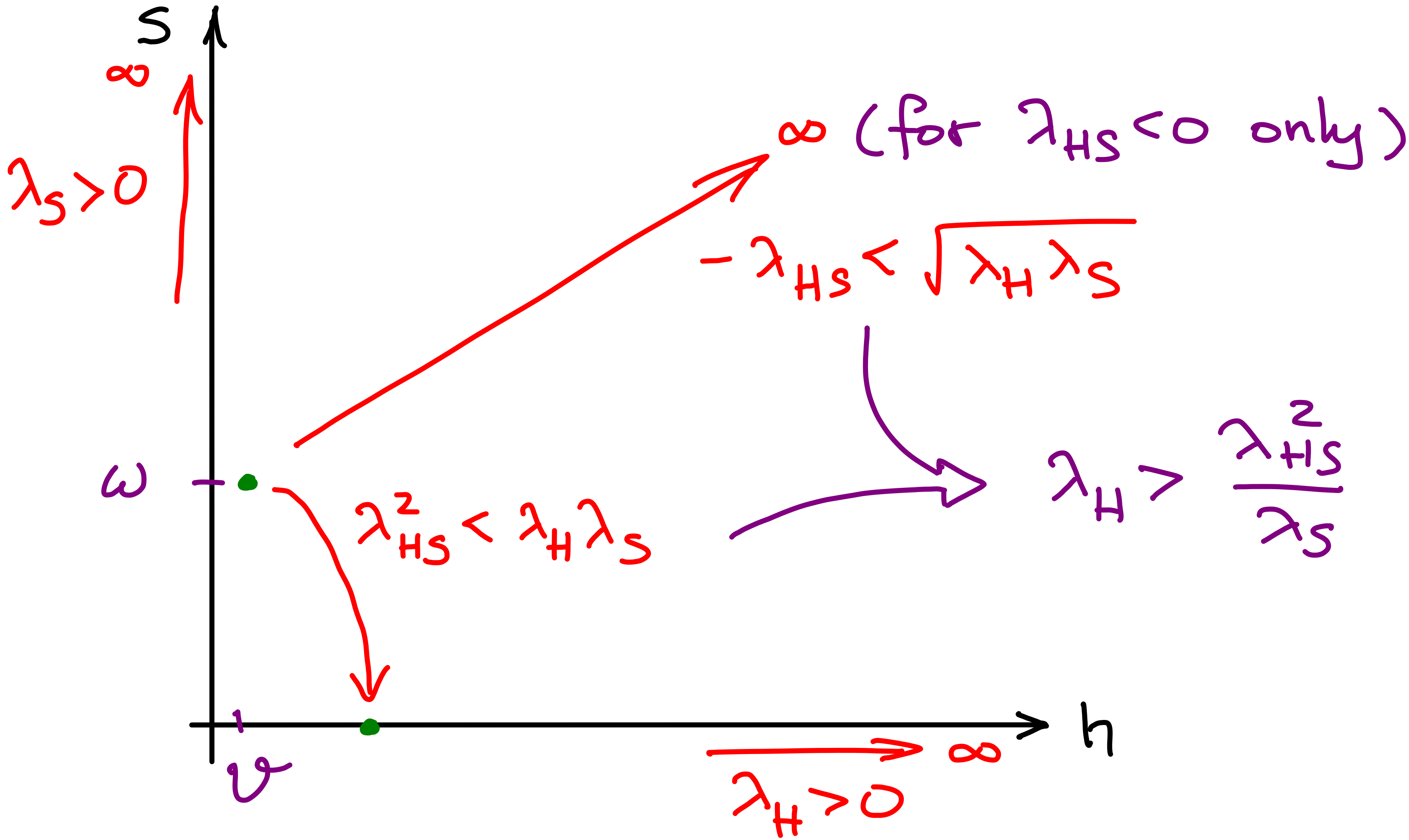
INGLET

Falling $\lambda(\mu)$

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

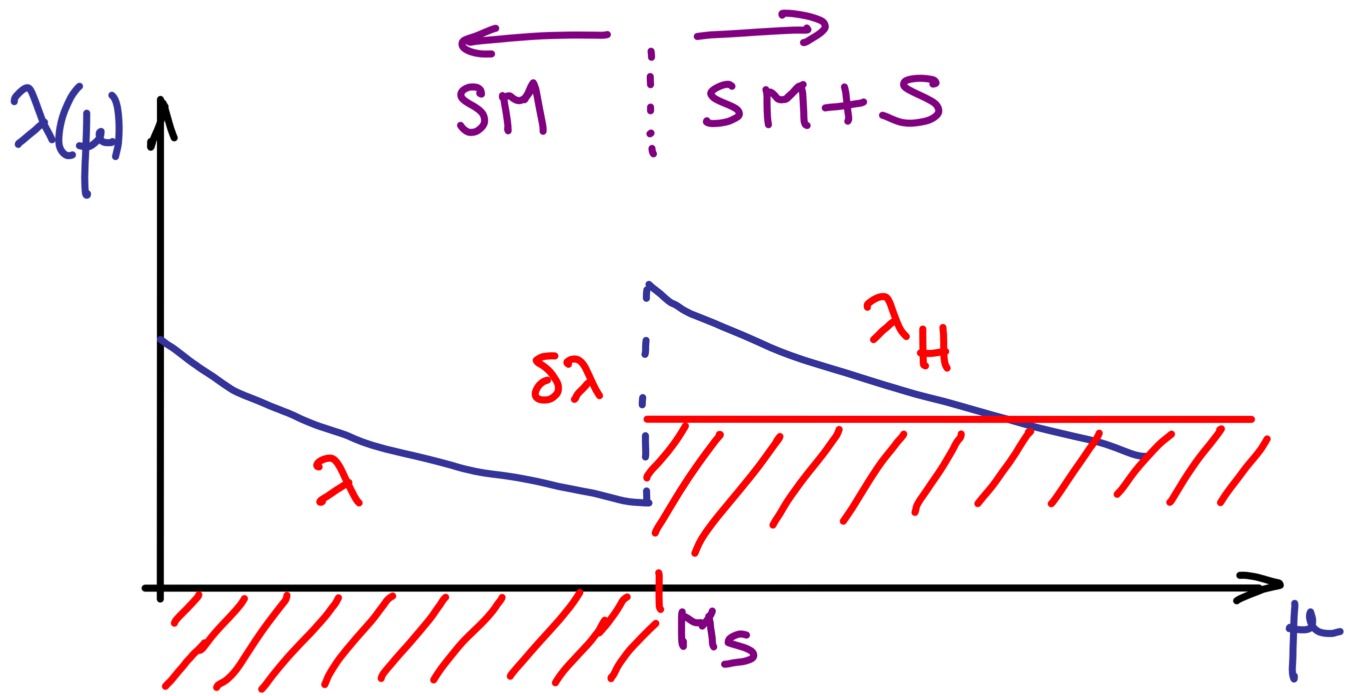
But, we must look more closely to stab. conditions

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

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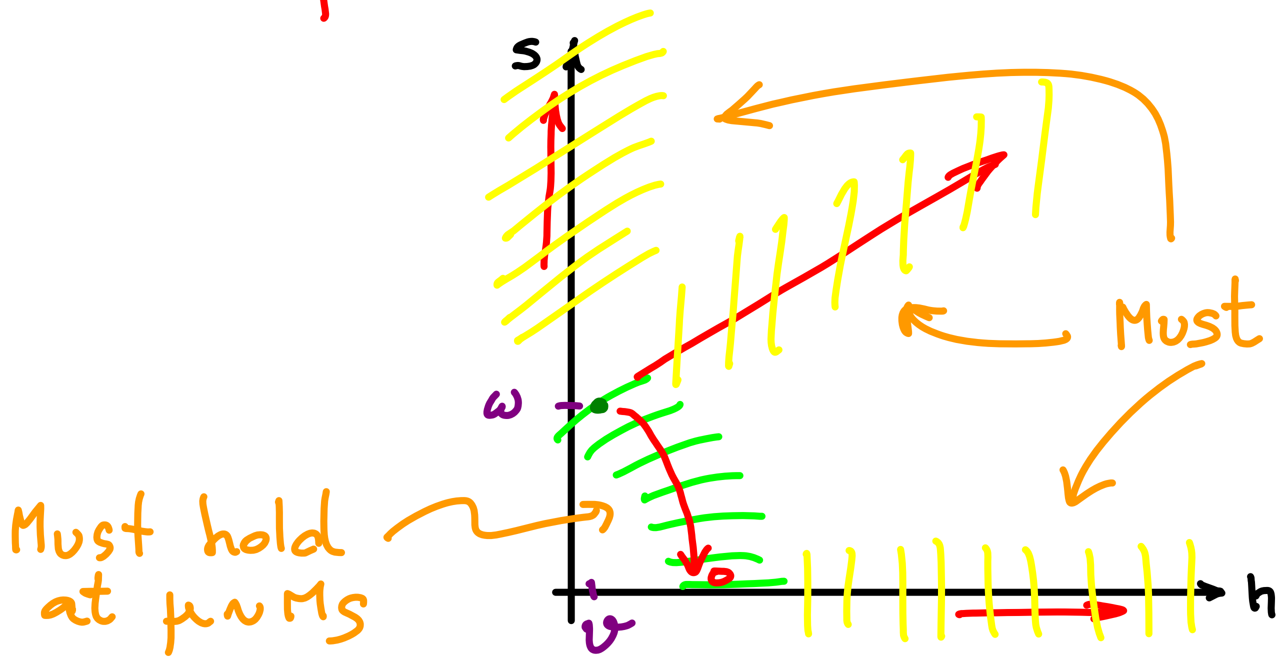
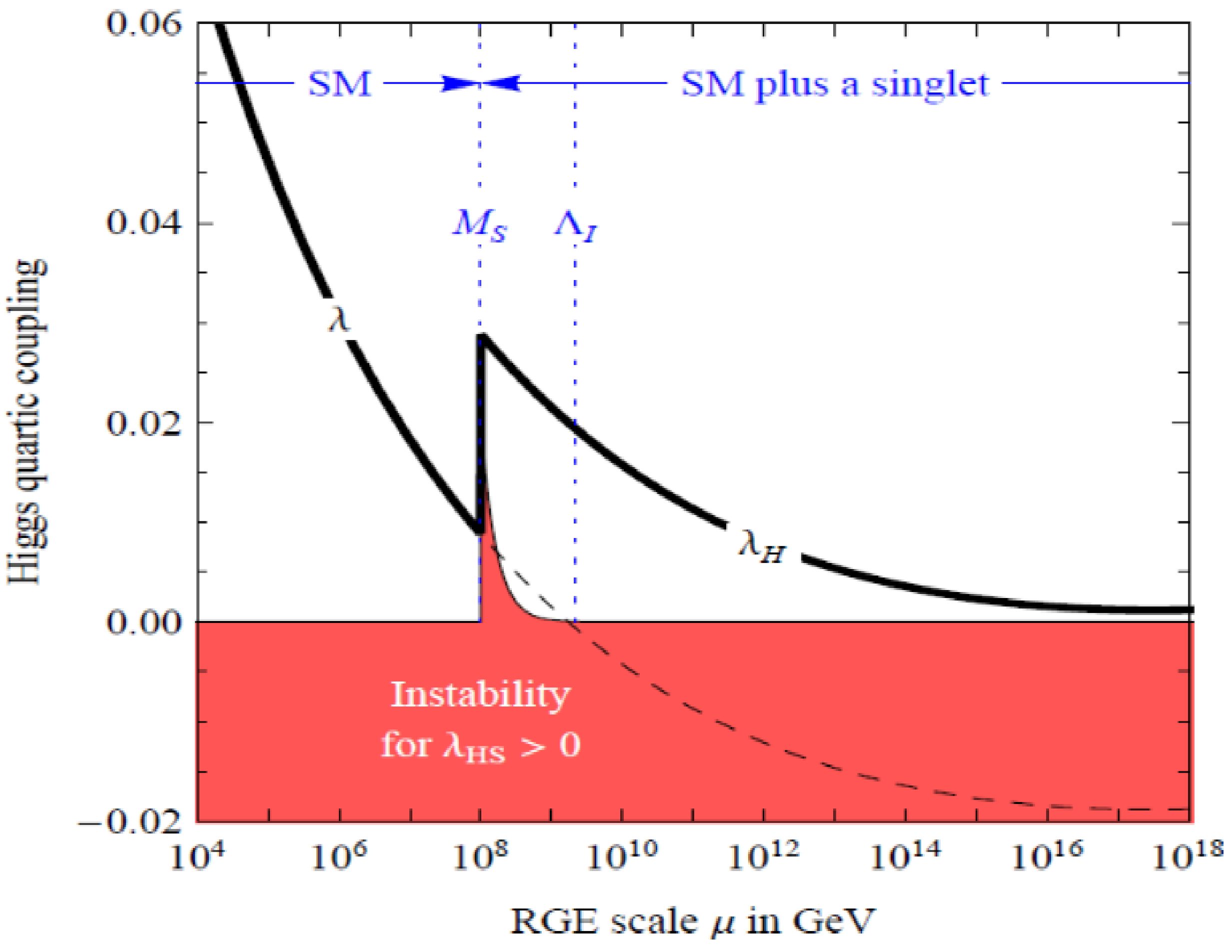
Scale-dependence is all-important in stab. conditions



$\lambda_{HS} > 0$

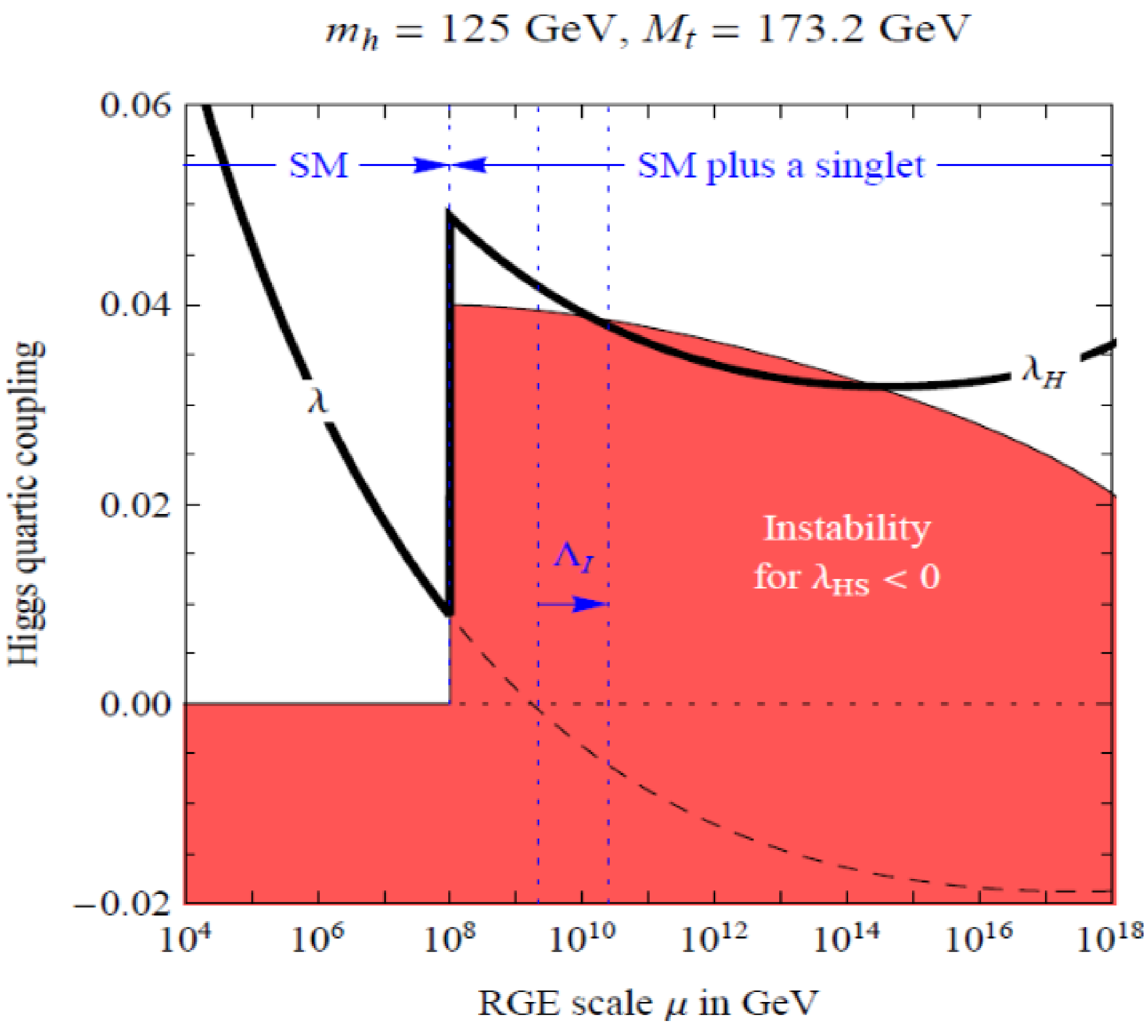
Need to enforce $\lambda_H > \lambda_{HS}^2 / \lambda_S$ only at low-energy for $\mu \sim M_S$

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

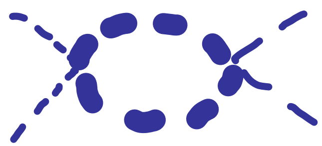


$\lambda_{HS} < 0$

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



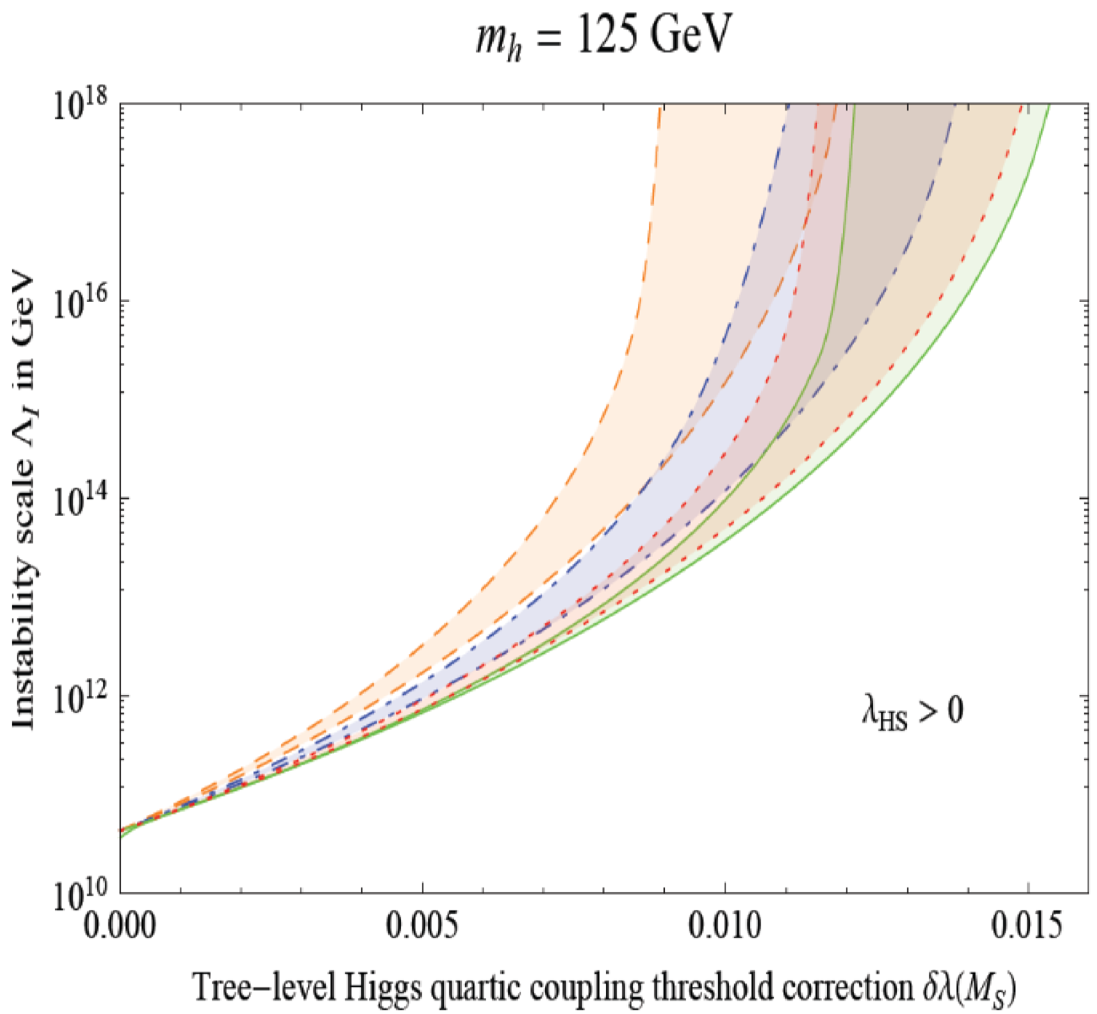
Effect now relies on loop effect



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

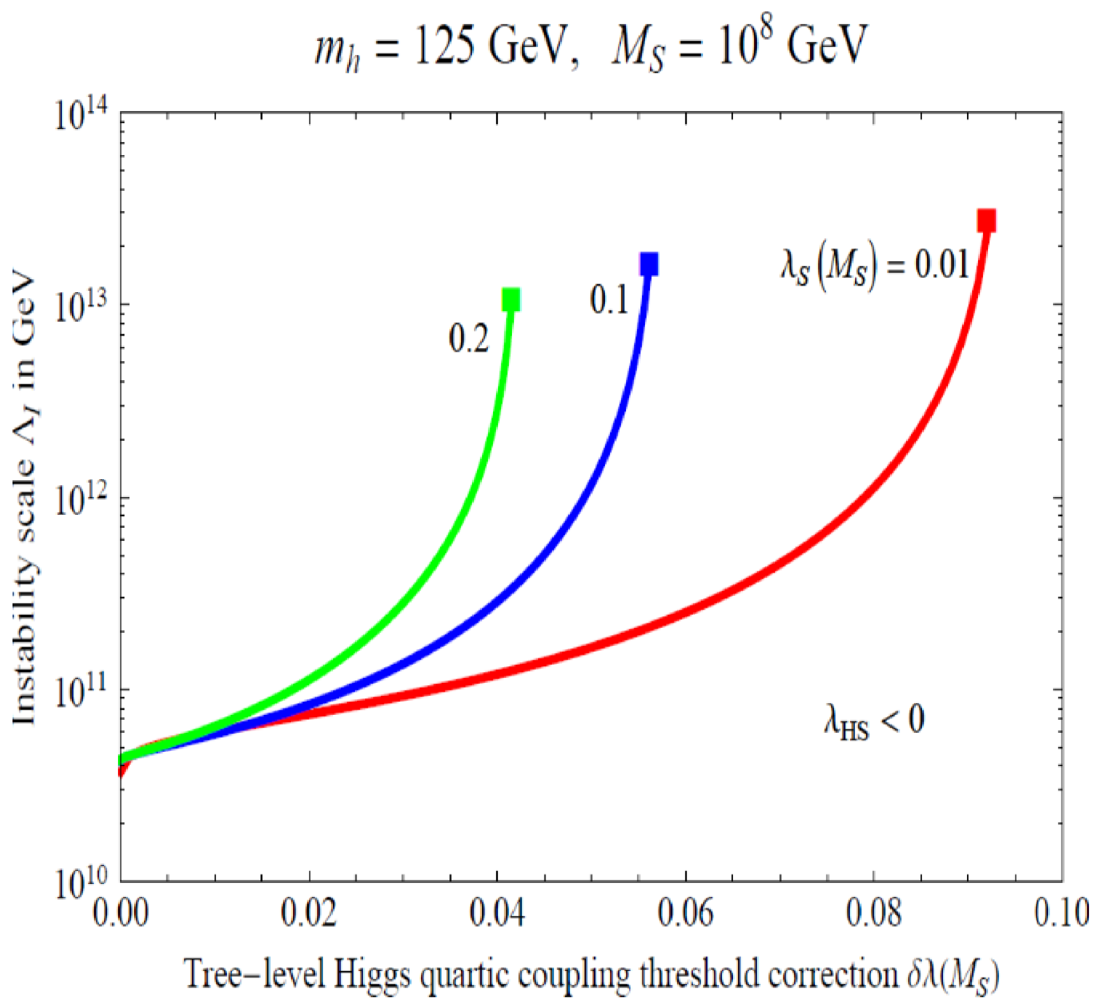
IMPACT ON INSTABILITY SCALE

$\lambda_{HS} > 0$



$\delta\lambda$

$\lambda_{HS} < 0$



$\delta\lambda$

IMPLEMENTATION IN MODELS

In our paper:

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

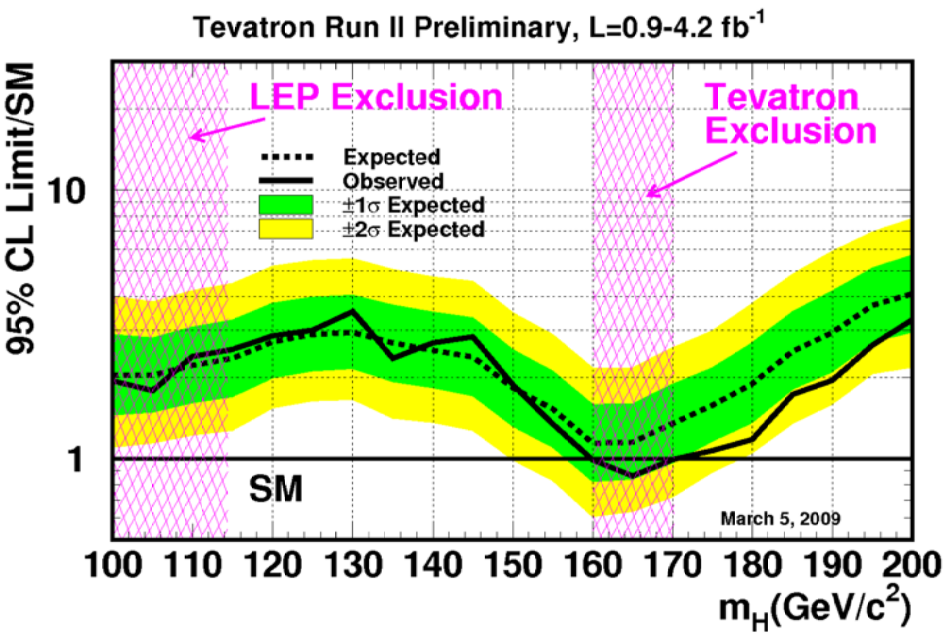
Later uses of the idea

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

IMPLEMENTATION IN MODELS

- Non-commutative SM   Chamseddine, Connes '12

  Predicted $M_h \simeq 170$ GeV



IMPLEMENTATION IN MODELS

- Non-commutative SM Chamseddine, Connes '12

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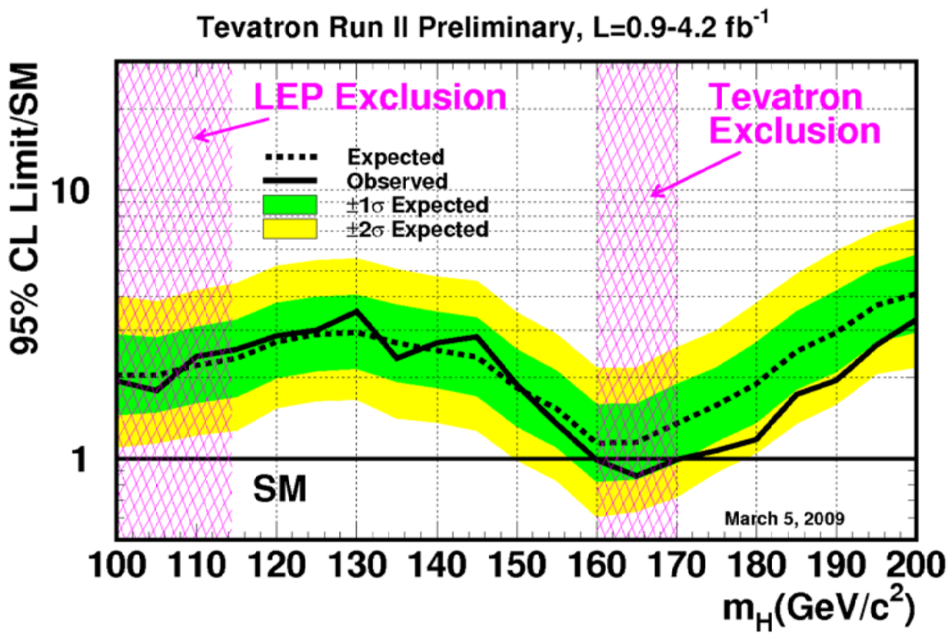
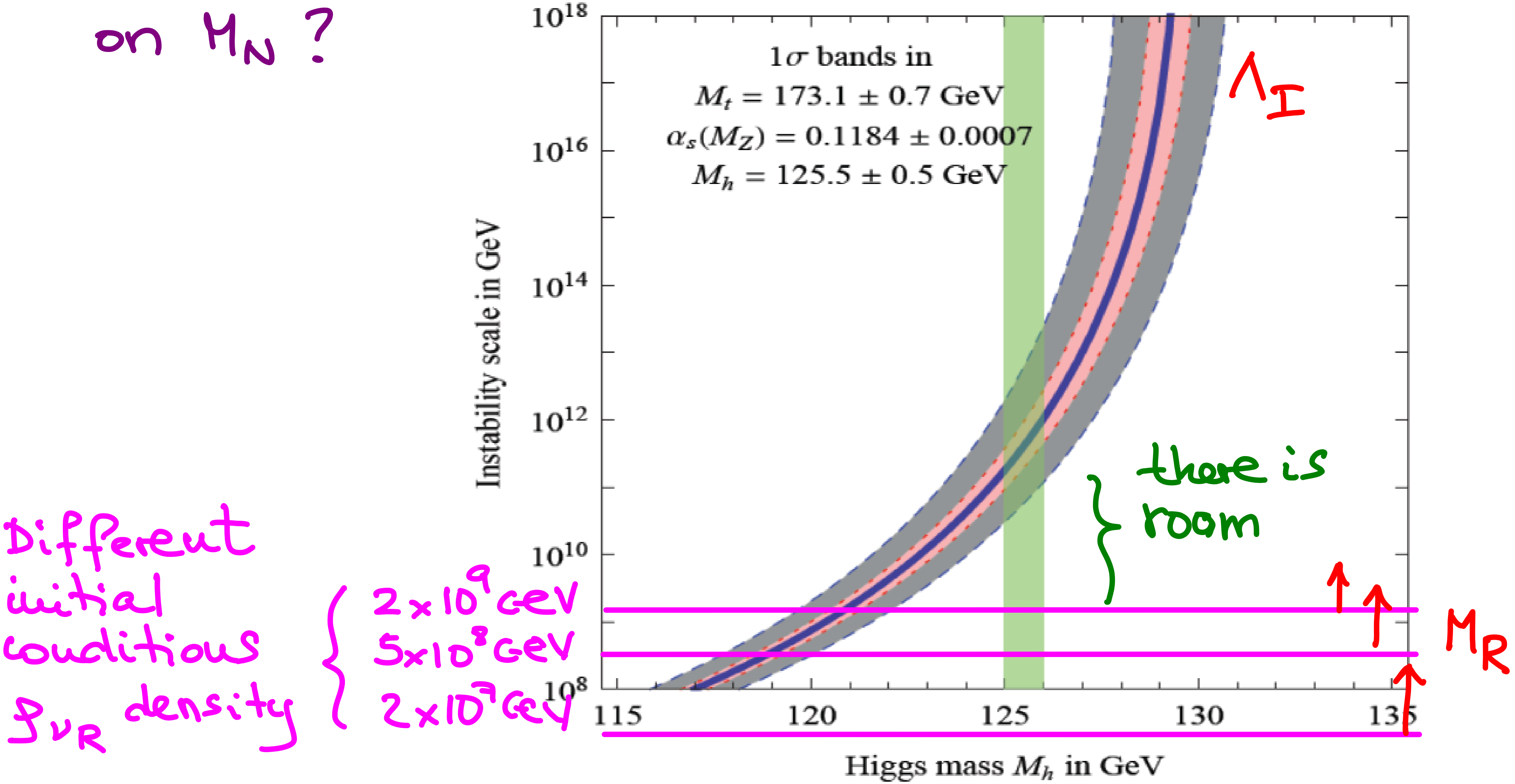


But the model had a singlet and could be resurrected!
Now $M_h \simeq 125$ GeV possible...

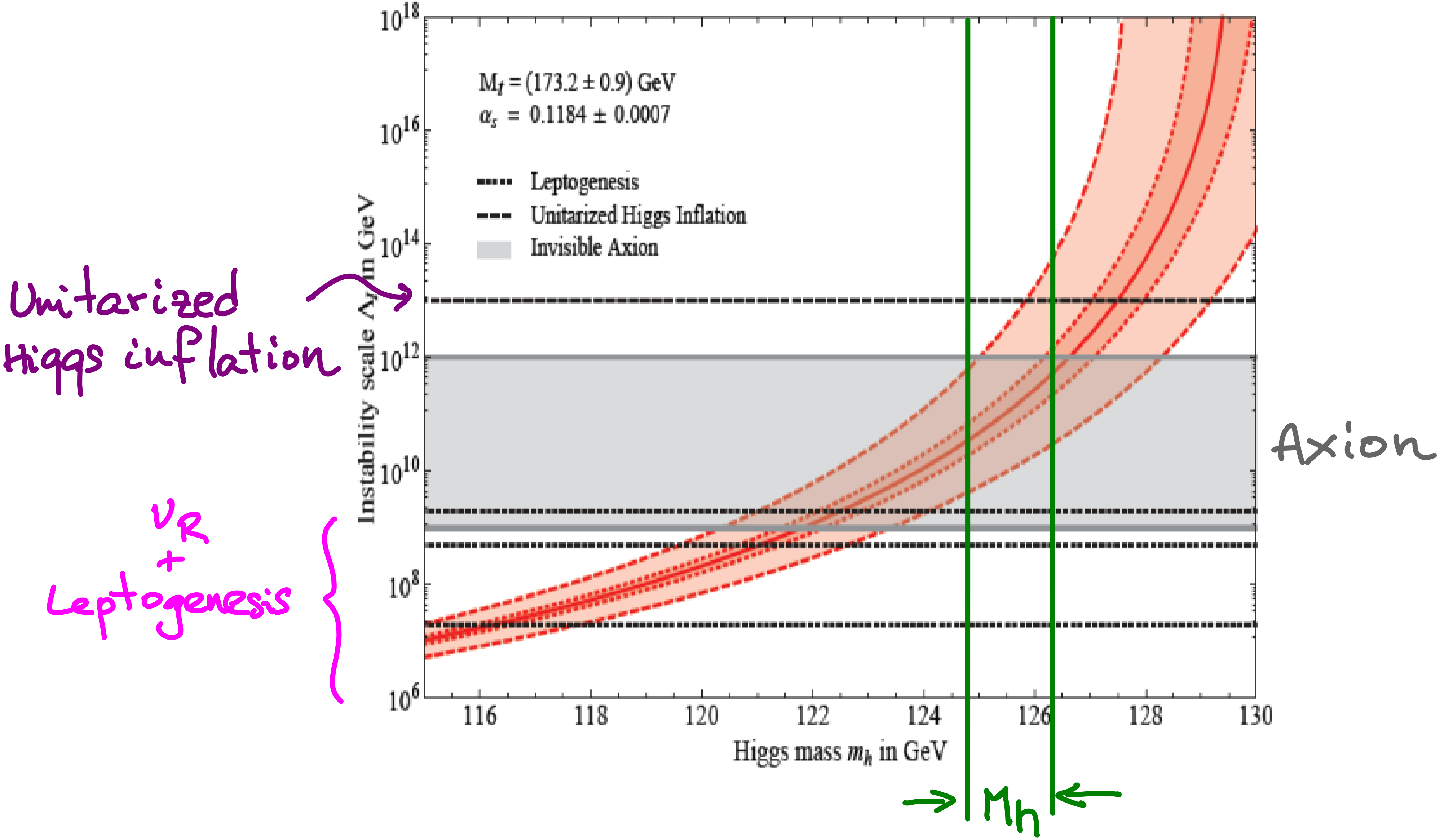
SEE-SAW IMPLEMENTATION

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

Is this compatible with leptogenesis constraints on M_N ?



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 in SM ($\Lambda_I \sim 10^{10}$ GeV)

EW vacuum is Long-lived and intriguingly close to stability boundary. Deep meaning of this?

This instability has implications for BSM, cosmology...

But let's hope for new physics at LHC-II!

NNLO INGREDIENTS

Renormalisation Group Equations

	LO 1 loop	NLO 2 loop	NNLO 3 loop	NNNLO 4 loop
g_3	full [53,54]	$\mathcal{O}(\alpha_3^2)$ [55,56] $\mathcal{O}(\alpha_3\alpha_{1,2})$ [61] full [63]	$\mathcal{O}(\alpha_3^3)$ [57,58] $\mathcal{O}(\alpha_3^2\alpha_t)$ [62] full [64,65]	$\mathcal{O}(\alpha_3^4)$ [59,60]
$g_{1,2}$	full [53,54]	full [63]	full [64,65]	—
y_t	full [66]	$\mathcal{O}(\alpha_t^2, \alpha_3\alpha_t)$ [67] full [70]	full [68,69]	—
λ, m^2	full [66]	full [71,72]	full [73,74]	—

Threshold corrections at the weak scale

	LO 0 loop	NLO 1 loop	NNLO 2 loop	NNNLO 3 loop
g_2	$2M_W/V$	full [75,76]	full [This work]	—
g_Y	$2\sqrt{M_Z^2 - M_W^2}/V$	full [75,76]	full [This work]	—
y_t	$\sqrt{2}M_t/V$	$\mathcal{O}(\alpha_3)$ [77] $\mathcal{O}(\alpha)$ [81]	$\mathcal{O}(\alpha_3^2, \alpha_3\alpha_{1,2})$ [34] full [This work]	$\mathcal{O}(\alpha_3^3)$ [78–80]
λ	$M_h^2/2V^2$	full [82]	for $g_{1,2} = 0$ [4] full [This work]	—
m^2	M_h^2	full [82]	full [This work]	—

Table 1: *Present status of higher-order computations included in our code. With the present paper the calculation of the SM parameters at NNLO precision is complete. Here we have defined* $V \equiv (\sqrt{2}G_\mu)^{-1/2}$ *and* $g_1 = \sqrt{5/3}g_Y$.

Buttazzo et al '13.

TOP MASS CAVEATS

Have assumed

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

from Tevatron + LHC is the top pole mass.

(compare with $M_t = 173.34 \pm 0.76$ GeV official comb.)

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

$$M_t = 171.2 \pm 3.1 \text{ GeV}$$

would still allow for stability

Alekhin, Djouadi, Moch '12

Too conservative given the good agreement...