Consequences of the Higgs discovery

[within and beyond the Standard Model]

Gino Isidori
[*INFN, Frascati*]

- Introduction
- A closer look to the SM Higgs sector
- The Higgs mass and the fate of the SM vacuum
- Higgs & SUSY
- What's next? Precision Higgs studies
- Conclusions

Consequences of the Higgs discovery
[within and beyond the Standard Model]:
a personal perspective...

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Introduction

All known phenomena in particle physics (*leaving aside a few cosmological observations*) can be described with good accuracy by a remarkably simple (*effective*) theory:

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs\ (Symm.\ Break.)}(\phi, A_a, \psi_i)$$

- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections (UV insensitive)
- Highly symmetric [*gauge + favor symmetries*]

- *Ad hoc*
- Necessary to describe data [*the electroweak symmetry forbid masses for all the elementary particles observed so far...*]
- Not stable with respect to quantum corrections (UV sensitive)
- Origin of the flavor structure of the model [*and of all the problems of the model...*]

Introduction

All known phenomena in particle physics (*leaving aside a few cosmological observations*) can be described with good accuracy by a remarkably simple (*effective*) theory:

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- *Natural*
- Experimentally tested with high accuracy

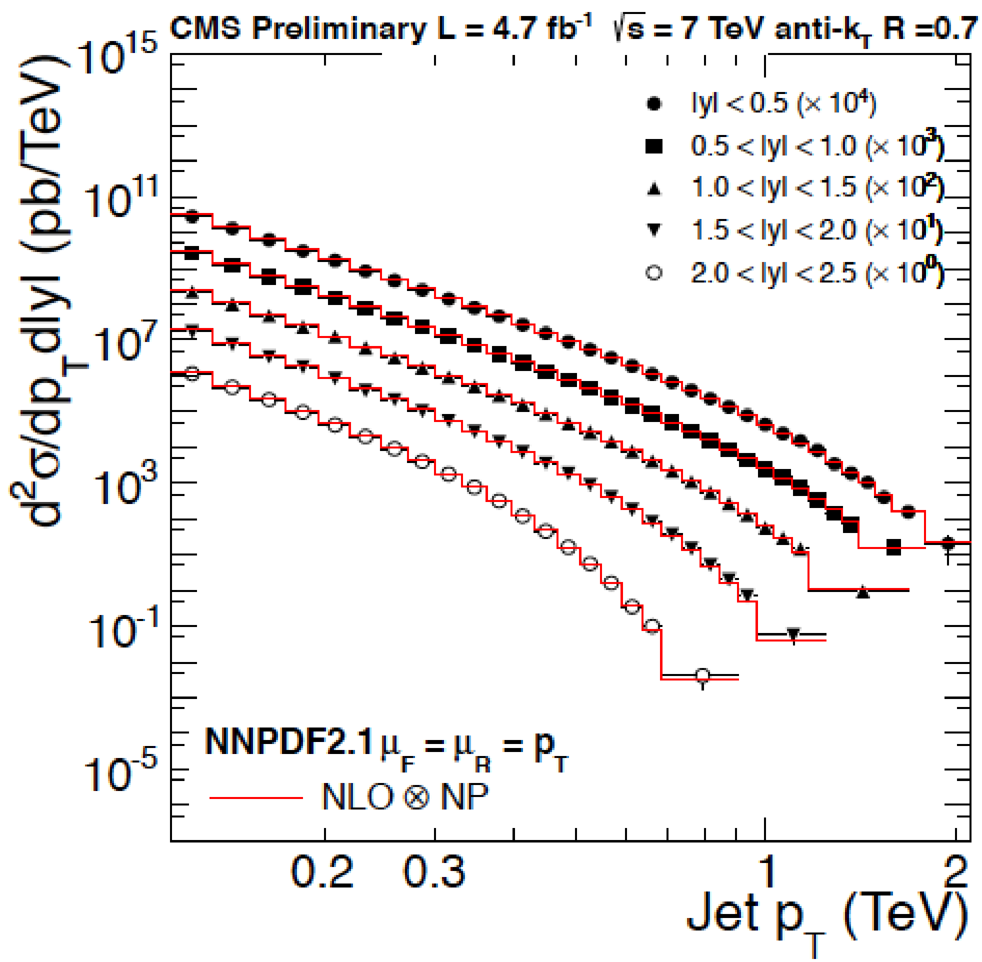
Elegant & stable, but also a bit boring...

- *Ad hoc*
- Necessary to describe data [*we couldn't live in a fully symmetric world...*]

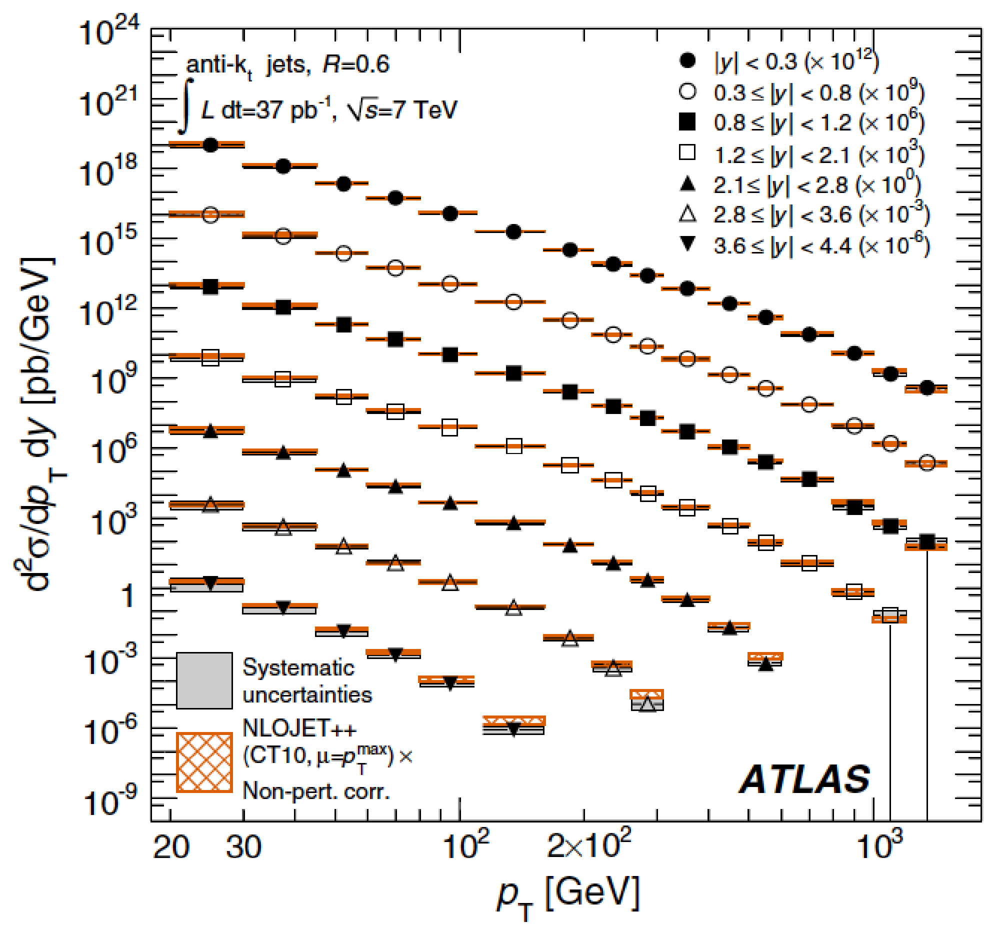
Ugly & unstable, but is what makes nature interesting...!

Introduction

LHC experiments have confirmed once more that we understand very well gauge interactions...

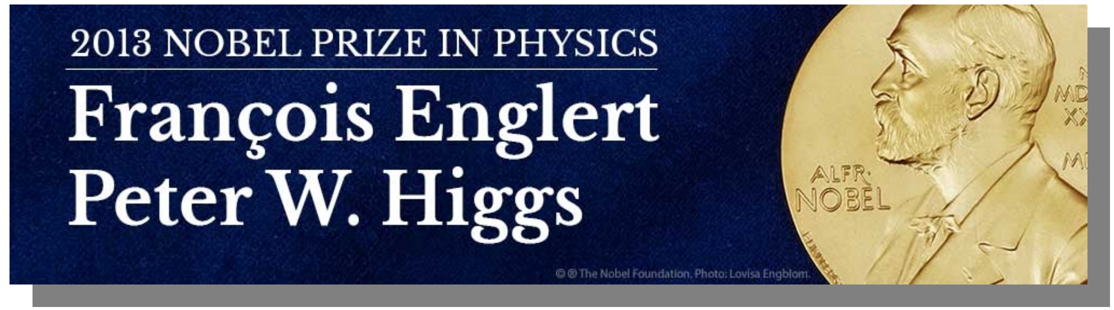


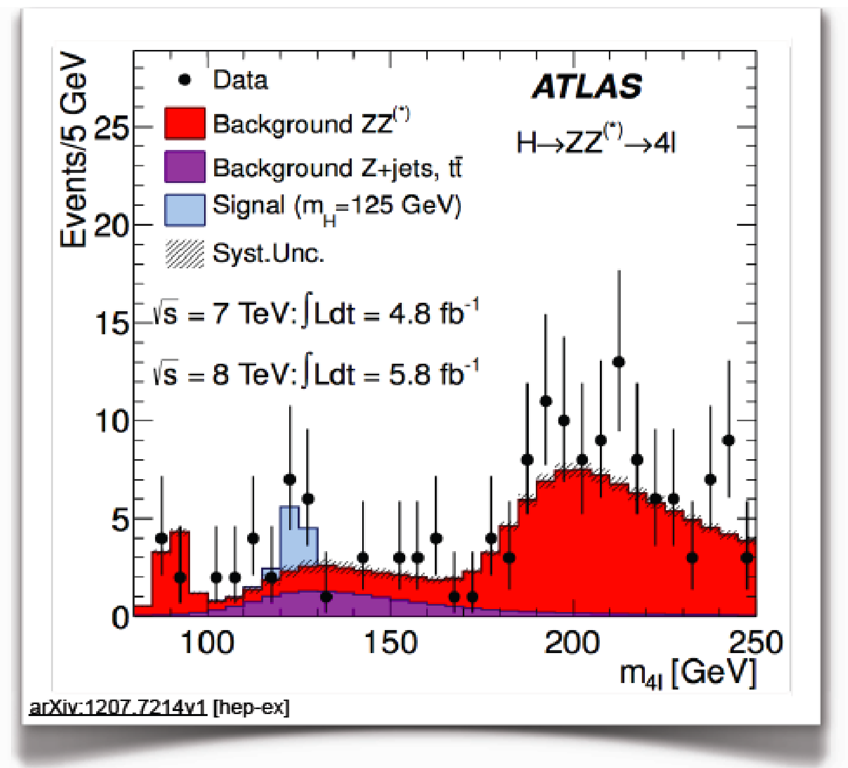
PHYSICAL REVIEW D **86,** 014022 (2012)



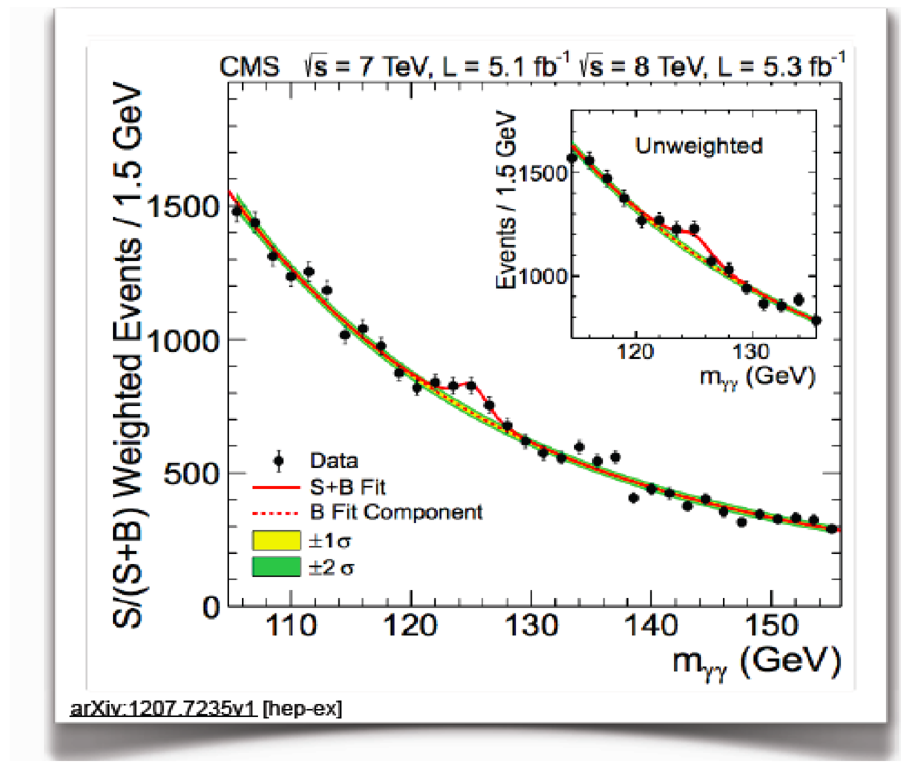
Introduction

...but the main result of the first LHC run is a deeper understanding of the <u>symmetry breaking sector</u> of the theory:





arXiv:1207.7214v1 [hep-ex]



arXiv:1207.7235v1 [hep-ex]

Clear evidence of a new particle <u>compatible</u> with the properties of the <u>Higgs boson</u>

Introduction

Still... the SM suffers of a series of theoretical & cosmological problems:

- Fine-tuning/UV sensitivity of the Higgs-mass term ["*hierarchy problem*"]
- Unexplained hierarchical structure of the Yukawa couplings ["*flavor puzzle*"]
- No explanation for the quantization of the U(1) charges [*hint of unification*?]
- No natural inclusion of neutrino masses [*hint of unification*?]
- Non coherent inclusion of gravity at the quantum level
- No good candidate for dark matter & no explanation of dark energy

⬇

Common view: the SM (and in particular the Higgs sector) is an *effective theory*, or the low-energy limit of a more fundamental theory, with new degrees of freedom at high energies.

Introduction

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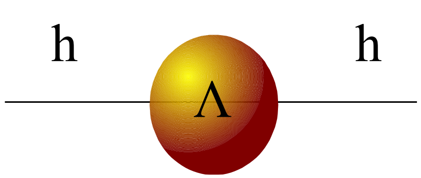
The only (*qualitative*) indication of NP around 1 TeV:



$\Delta m_h^2 \sim \Lambda^2$

Introduction

Before the Higgs discovery there were strong hopes that knowing the Higgs mass we would have gained a clear clue about the nature of physics beyond the Standard Model

These hopes were justified, and indeed m_h *could have* given us unambiguous answers...

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…however, the measured value resembles very much the typical "sibylline answer" of the ancient oracles.

Such as

Ibis redibis non morieris in bello

→ *You will go, be back, and not die in the battle*

→ *You will go, not be back, and die in the battle*

Introduction

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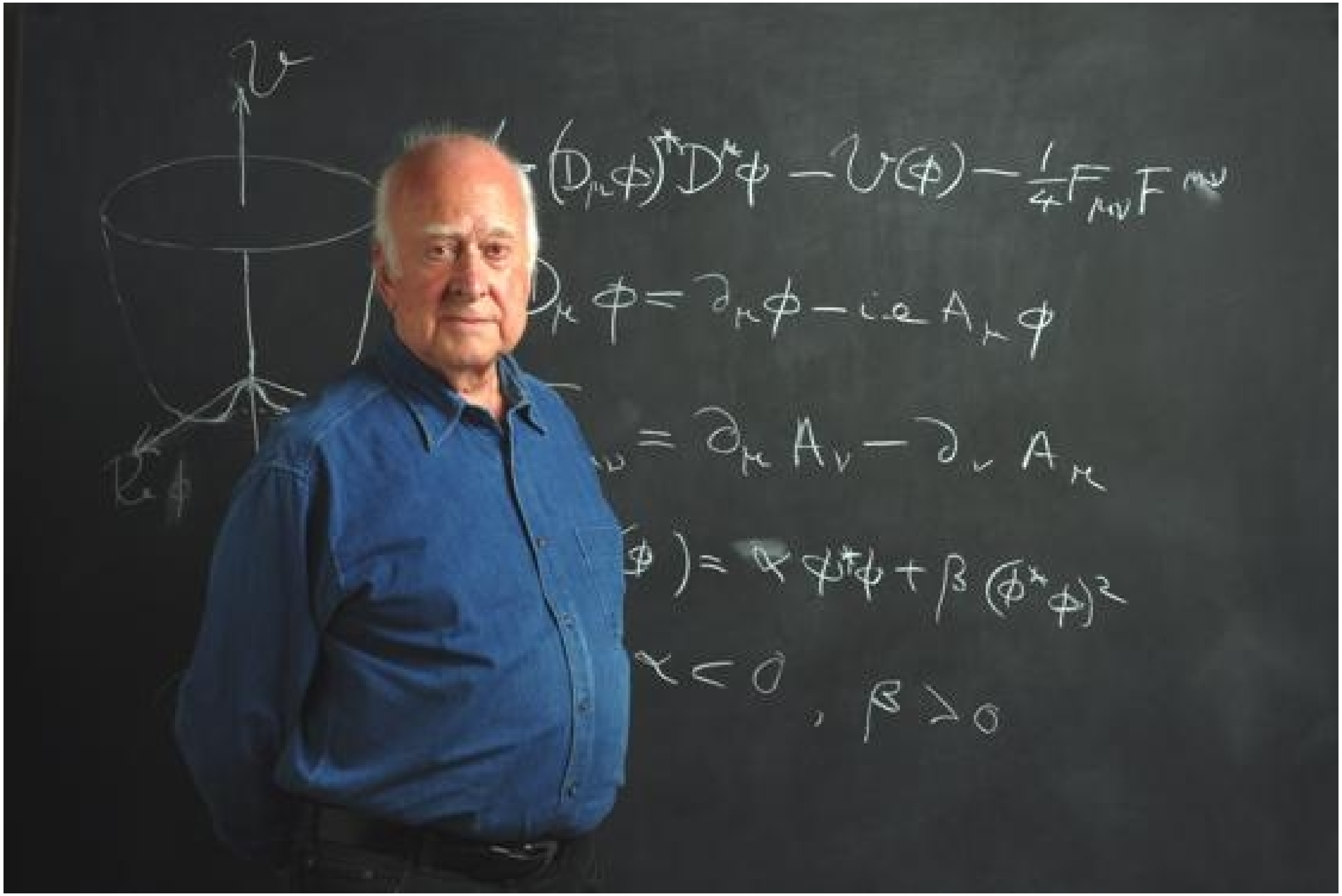
As I will illustrate in this talk, it is hard to conceive a more intricate/ambiguous situation concerning possible UV extensions of the SM than the one we have after the LHC8 results:

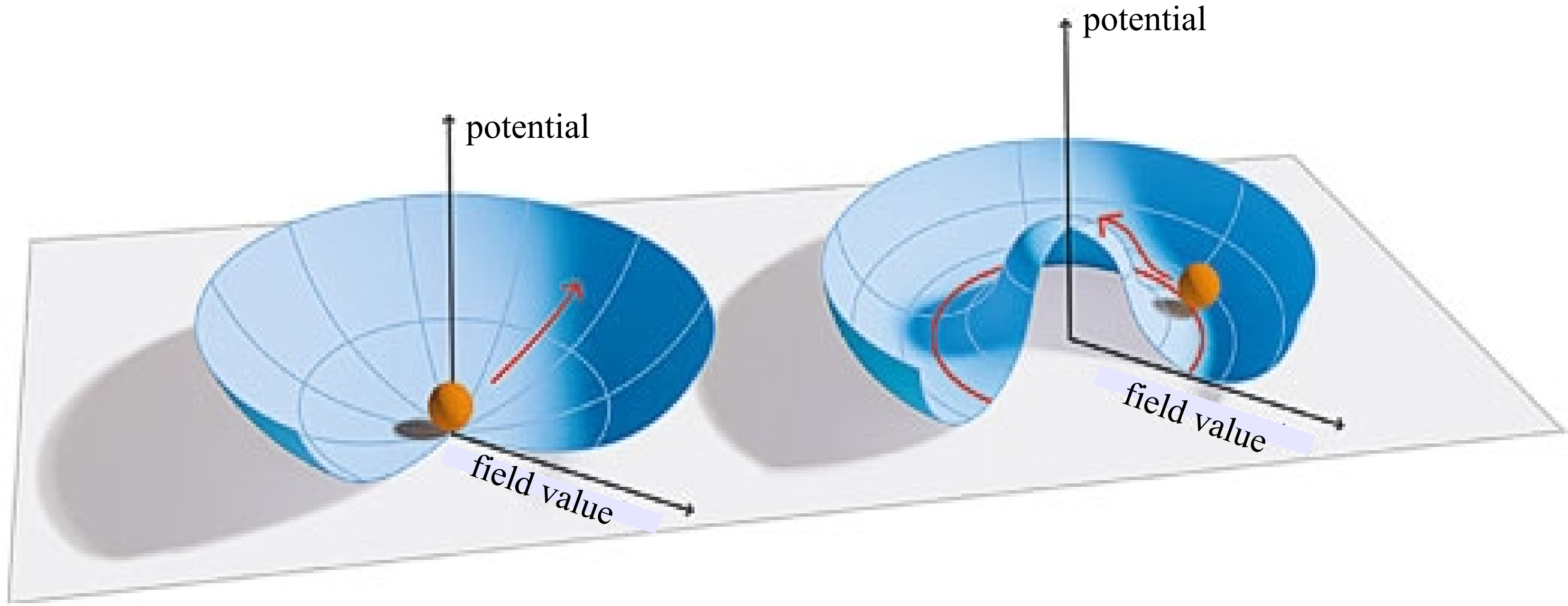
- $m_h = 125 – 126$ GeV
- no evidences of physics beyond the SM @ LHC8

▶ *A closer look to the SM Higgs sector*



A closer look to the SM Higgs sector

The Higgs mechanism, namely the introduction of an elementary $SU(2)_L$ scalar doublet, with ϕ^4 potential, is the most economical & simple choice to achieve the spontaneous symmetry breaking of both gauge [$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$] and flavor symmetries that we observe in nature.



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$$\mathscr{L}_{higgs}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, \phi$$

Before the start of the LHC only the ground state determined by this potential (*and the corresponding Goldstone boson structure*) was tested with good accuracy:

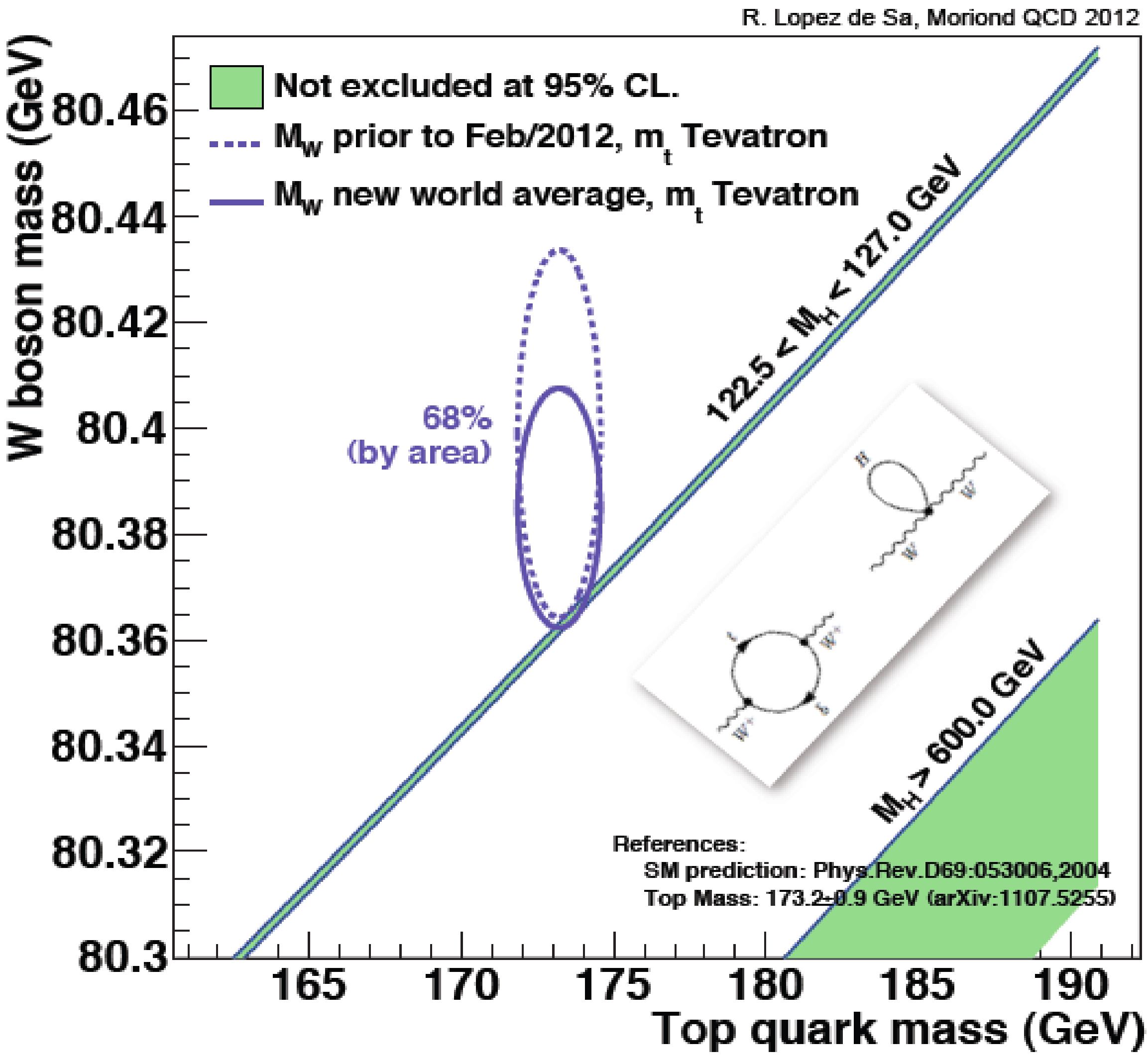
$$v = \langle\phi^+\phi\rangle^{1/2} \sim 246\ \mathrm{GeV} \quad [\, m_W = \tfrac{1}{2}\, g\, v \,]$$

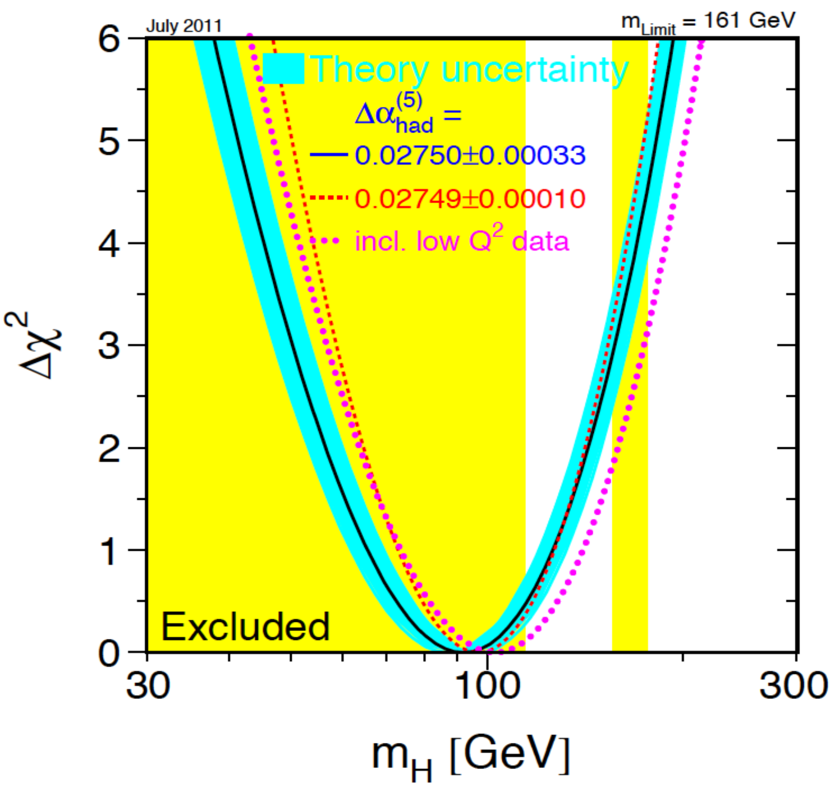
The situation has substantially changed about one year ago, with the observation of the 4th degree of freedom of the Higgs field (or its *massive excitation*):

$$\lambda_{(tree)} = \tfrac{1}{2}\, m_h^{\,2} / v^2 \approx 0.13 \qquad\qquad \mu^2_{\,(tree)} = \tfrac{1}{2}\, m_h^{\,2}$$

A closer look to the SM Higgs sector

Actually some information about the Higgs mass was already present in the e.w. precision tests (*assuming the validity of the SM up to high scales*):





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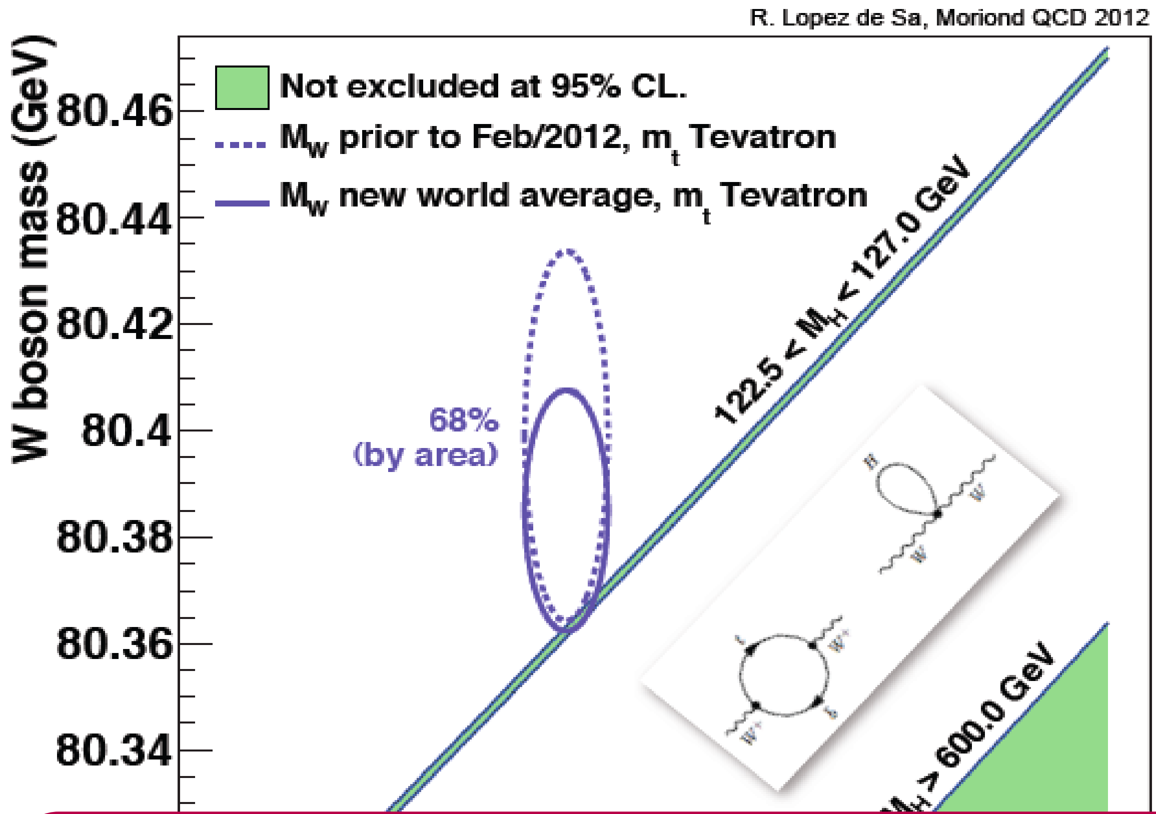
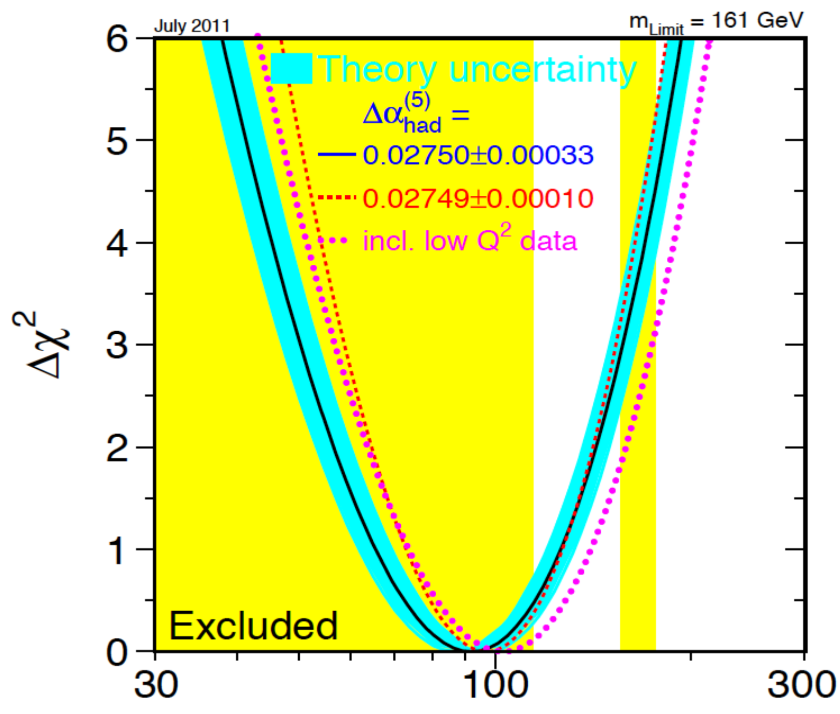
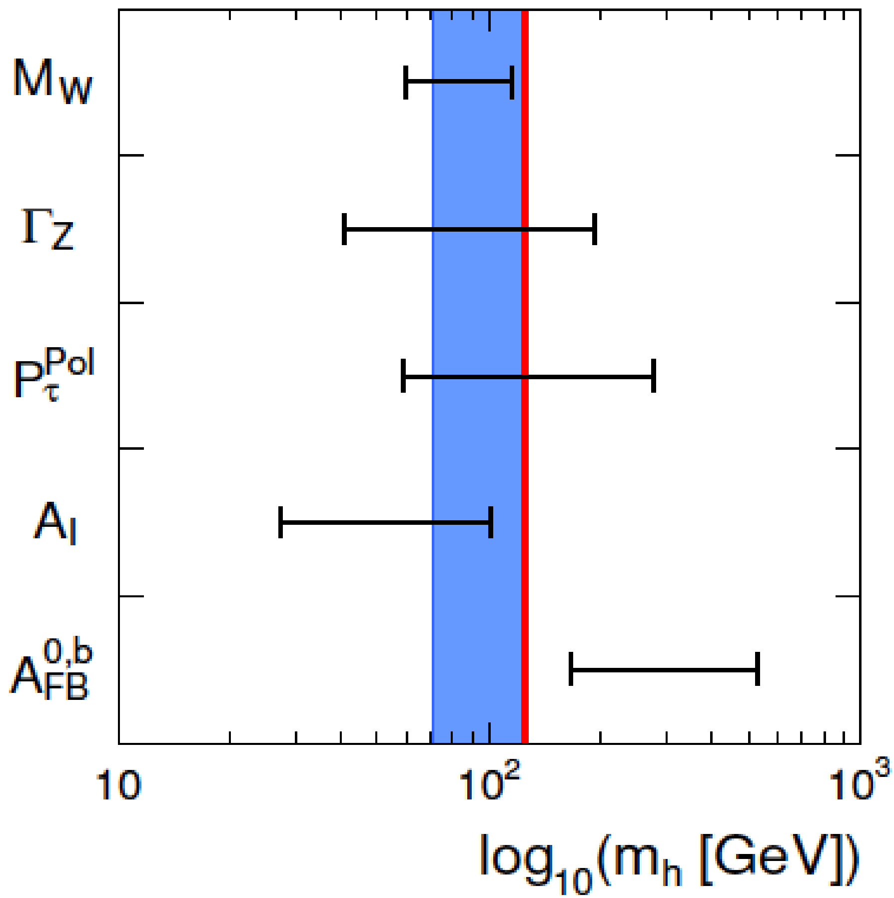




Message n.1: The observation of the physical Higgs boson with m_h well consistent with the (indirect) prediction of the e.w. precision tests is a *great success of the SM !*

A closer look to the SM Higgs sector

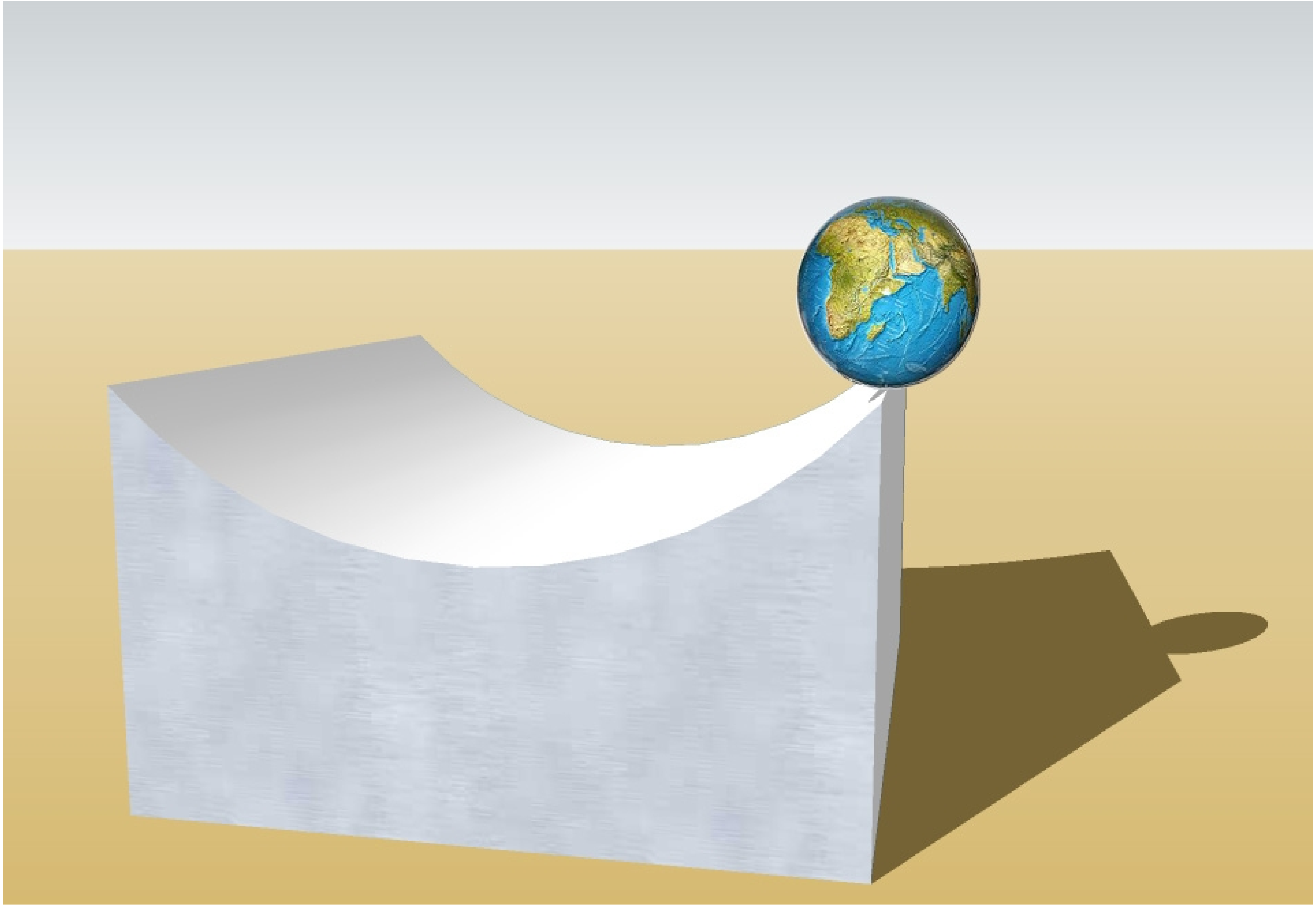


Ciuchini, Franco, Mishima, Silvestrini, '13

More generally, we have a strong indication that the symmetry breaking sector of the theory has a *minimal* and *weakly coupled* structure (at least around the TeV scale), as in the SM.

Message n.1: The observation of the physical Higgs boson with m_h well consistent with the (indirect) prediction of the e.w. precision tests is a *great success of the SM !*

▶ *The Higgs mass and the fate of the SM vacuum*

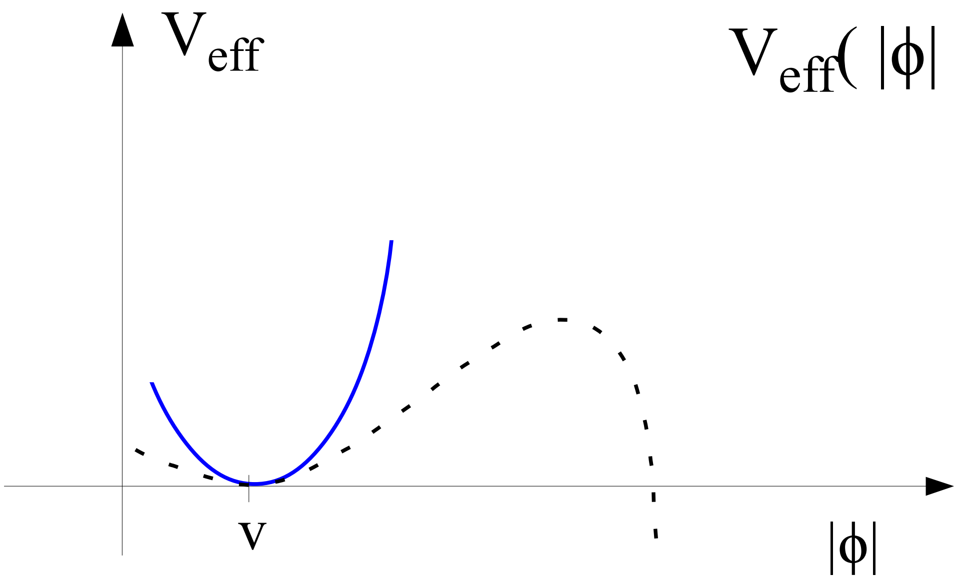


The Higgs mass and the fate of the SM vacuum

In principle, an unambiguous indication for New Physics (and an upper bound on the NP scale) could have been obtained by the high-energy behavior of the Higgs potential:

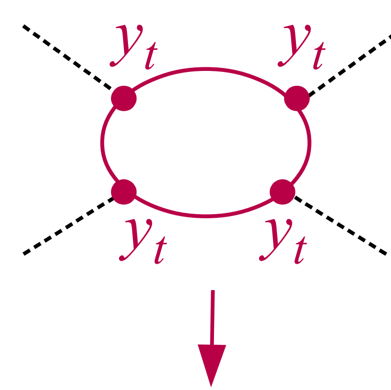
At large field values:

$$V_{eff}(\, |\phi| \gg v \,) \approx \lambda(|\phi|) \times |\phi|^4 + O(v^2|\phi|^2)$$



$$\lambda(v) \propto \frac{m_h^2}{v^2}$$

$$y_t(v) \propto \frac{m_t}{v}$$



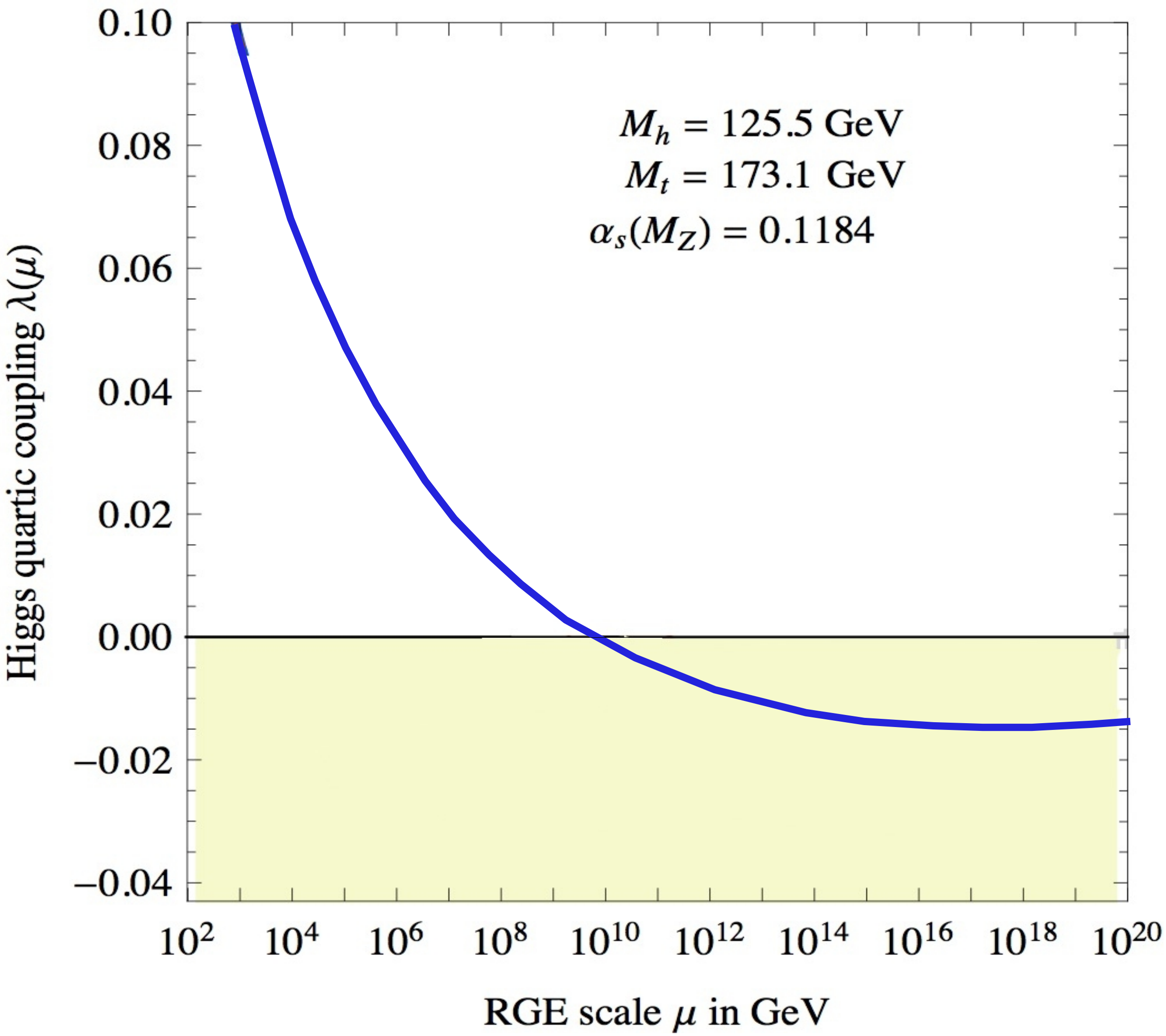
decreasing λ at large energies

A too-light m_h could imply an unstable Higgs potential → need for NP

Cabibbo, Maiani, Parisi, Petronzio, '79; Hung '79; Lindner 86; Sher '89; ....

▶ *The Higgs mass and the fate of the SM vacuum*

This is indeed what happens for $m_h \approx 125$ GeV and $m_t \approx 173$ GeV !



The Higgs mass and the fate of the SM vacuum

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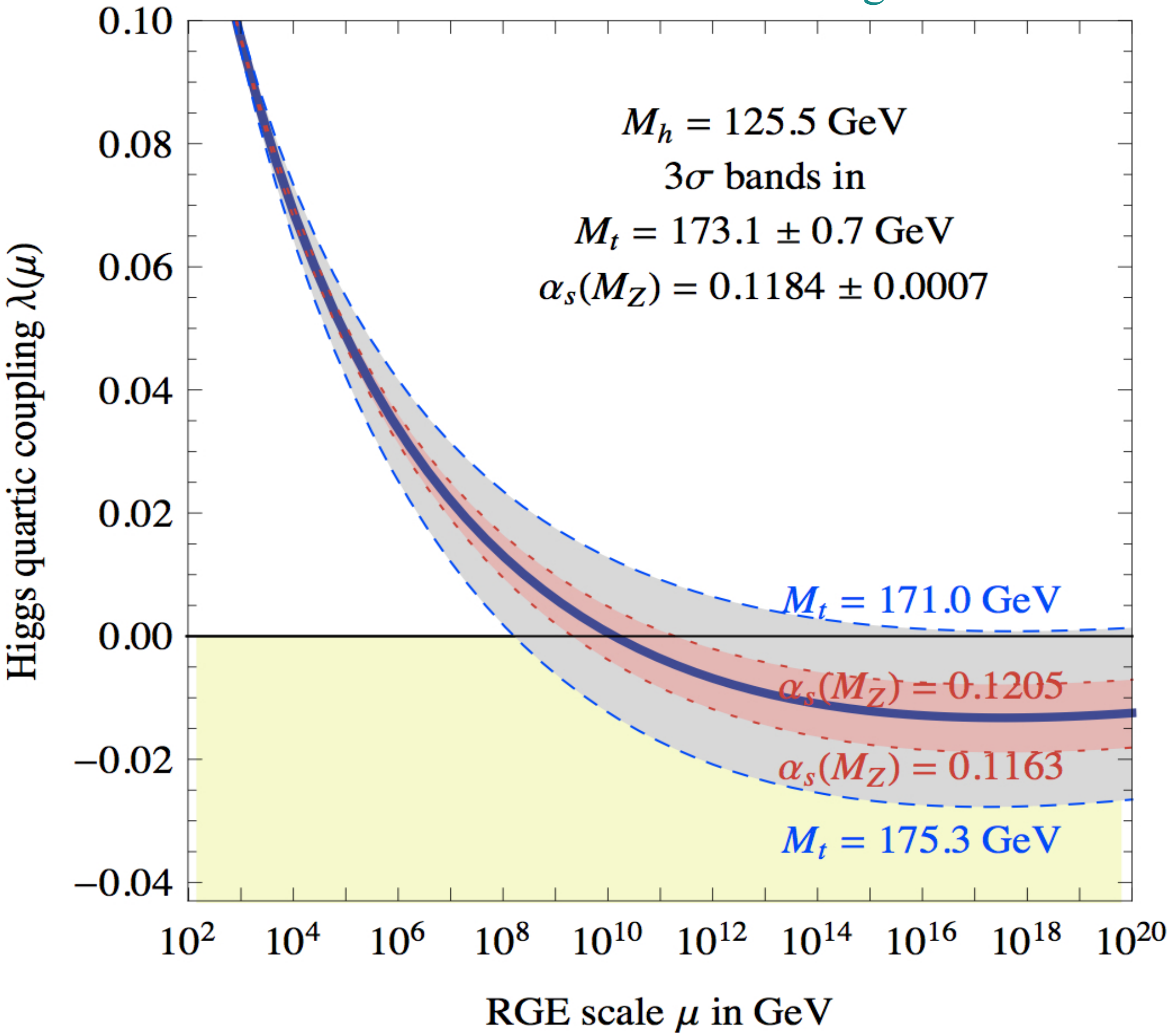
Degrassi *et al.* '12



...however, unfortunately (?) this is not enough to unambiguously claim the need of NP:

- The present error on m_t does not allow us to exclude at more than 3σ that $\lambda > 0$ up to M_{Planck}

- Even for the central values of m_h and m_t, the Higgs potential remains sufficiently metastable

The Higgs mass and the fate of the SM vacuum

The metastability condition: even if the potential has a second deeper minimum, the model is consistent with observations (= no need for NP) if the lifetime of the (unstable) e.w. minimum is longer than the age of the Universe

The e.w. minimum is destabilized by:

Quantum fluctuations (at T=0)

computable in a model-independent way

Thermal fluctuations

the probability depends on the thermal history of the universe & competes with the quantum tunneling only for very high T

The Higgs mass and the fate of the SM vacuum

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The e.w. minimum is destabilized by:

Quantum fluctuations (at T=0)

computable in a model-independent way

↓

Most conservative bound

Thermal fluctuations

the probability depends on the thermal history of the universe & competes with the quantum tunneling only for very high T

$$p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(1/R)|} + \begin{matrix}\text{tiny}\\ \text{higher-order}\\ \text{terms}\end{matrix} \right]$$

G.I., Ridolfi, Strumia '01

The tunneling is dominated by "bounces" of size R, such that λ(1/R) reaches its minimum value: λ can become negative, provided it remains small in magnitude.

The Higgs mass and the fate of the SM vacuum

The metastability condition

$$p \approx \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3|\lambda(1/R)|} \right]$$

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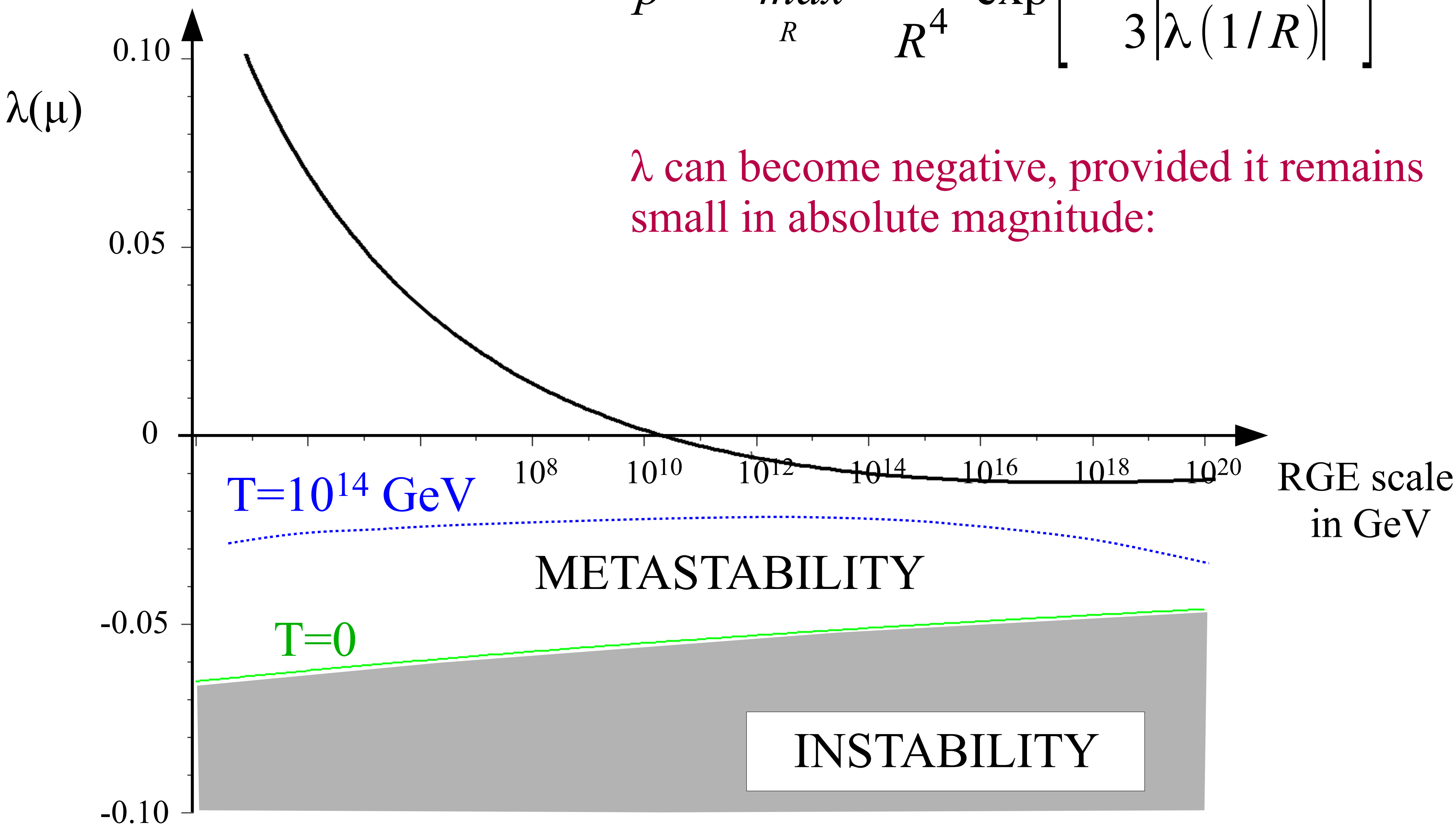
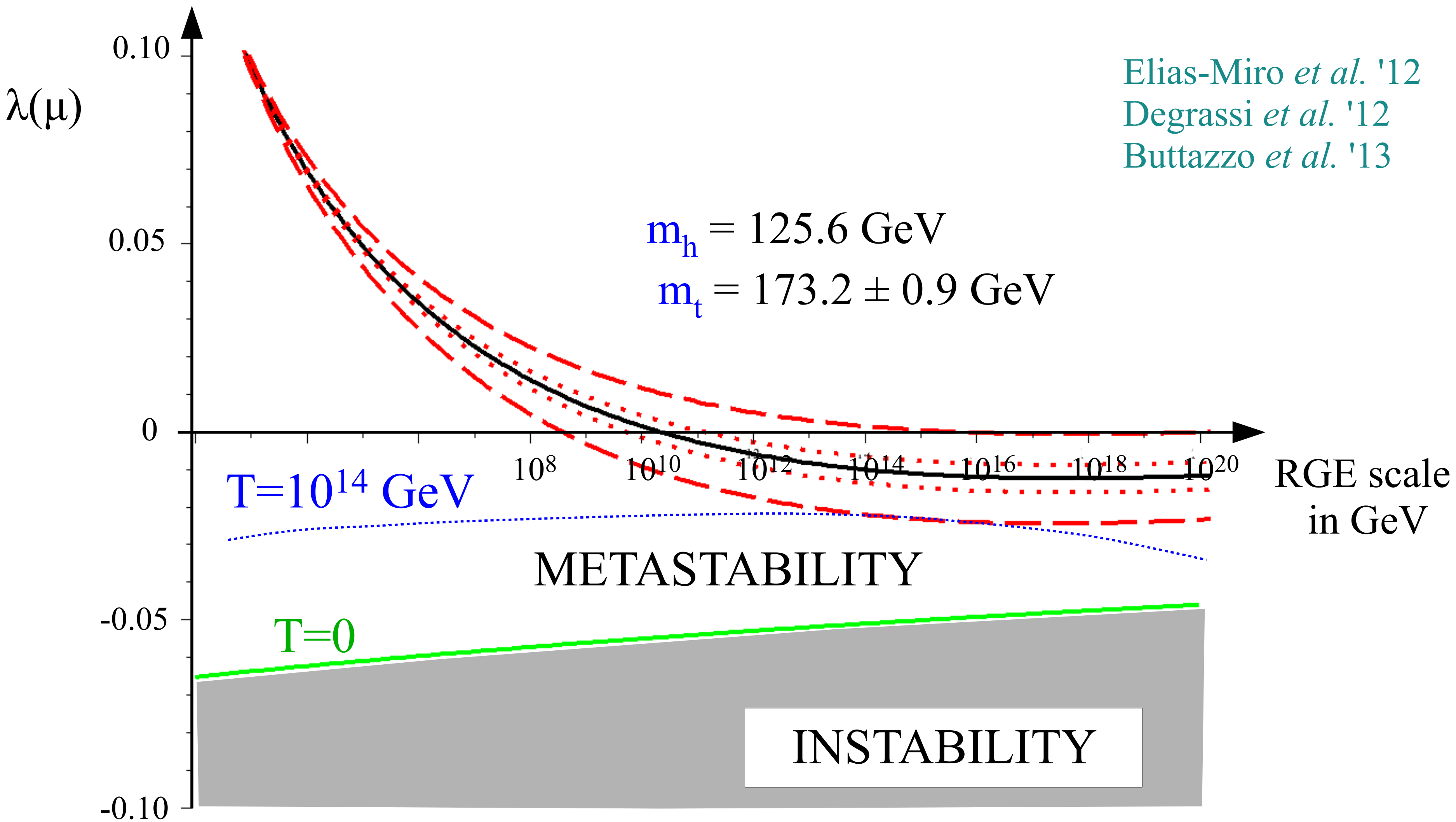


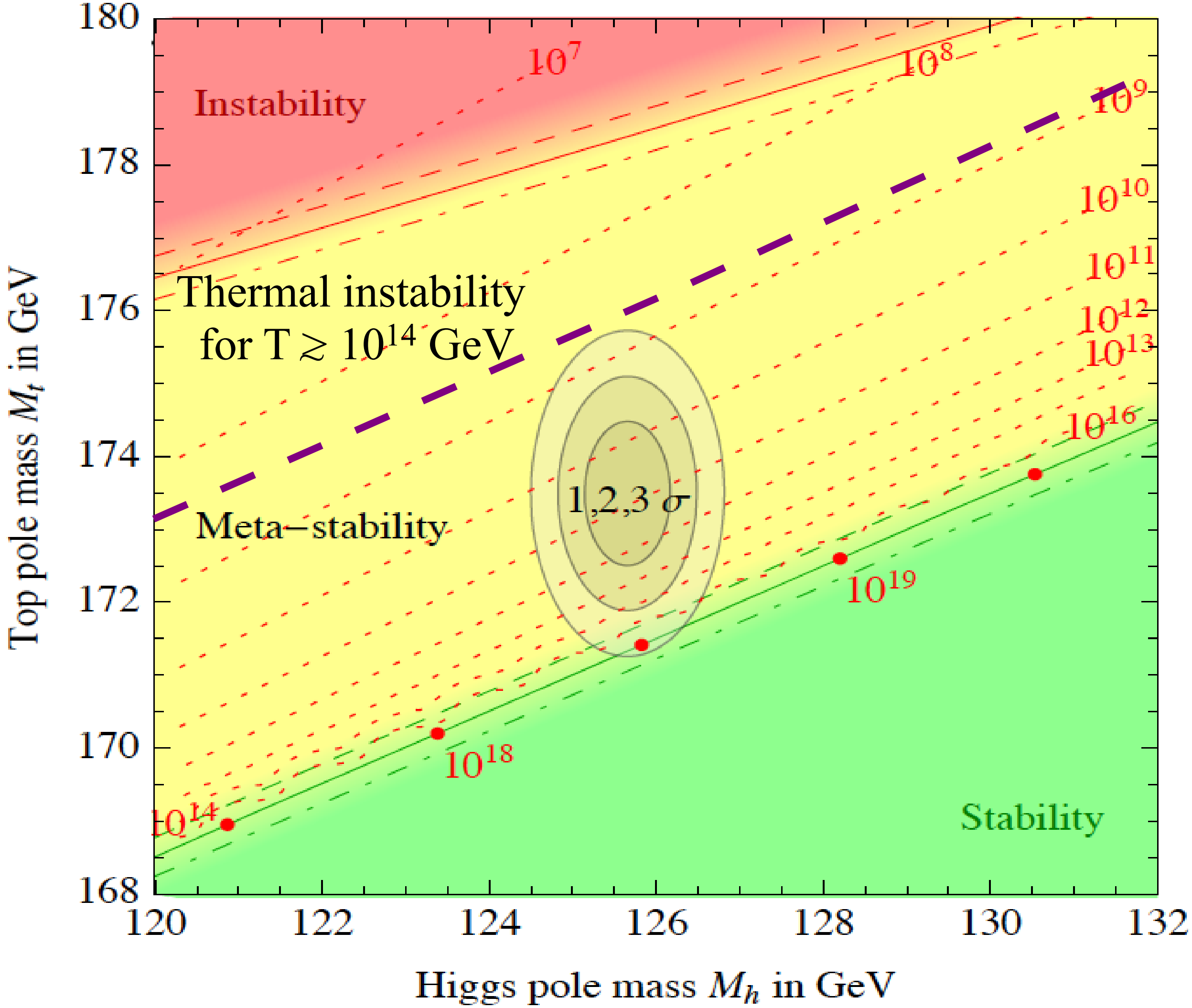
Message n.2: For $m_h \approx$ 125-126 GeV and the present central value of m_{top}, the SM vacuum is unstable but sufficiently long-lived, compared to the age of the Universe → no need of NP below M_{Pl} to stabilize the SM vacuum



The Higgs mass and the fate of the SM vacuum

The relation between Higgs and top masses from vacuum stability is now known at the NNLO accuracy, with a negligible theoretical error:

Degrassi et al. '12, Buttazzo *et al.* '13



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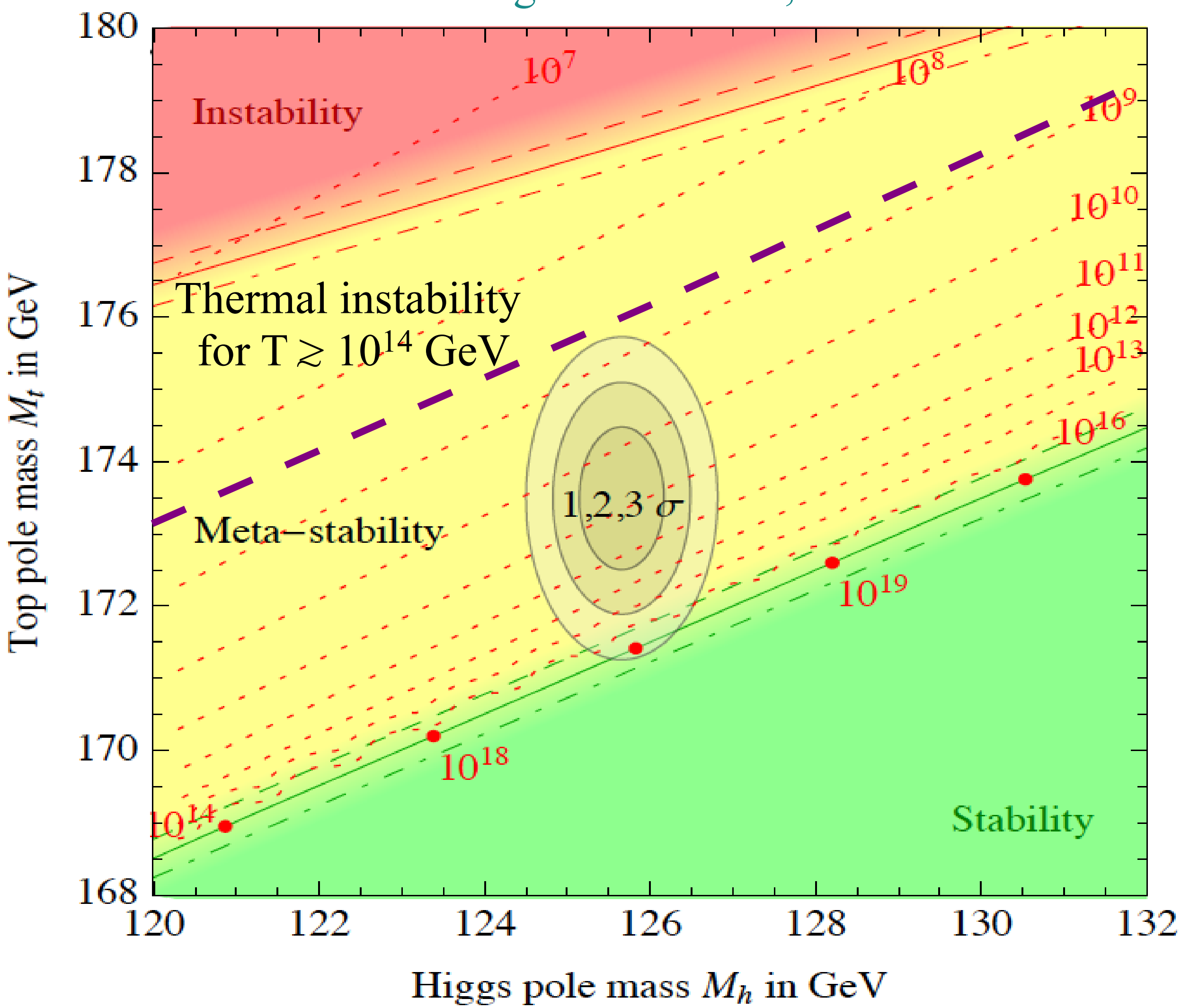


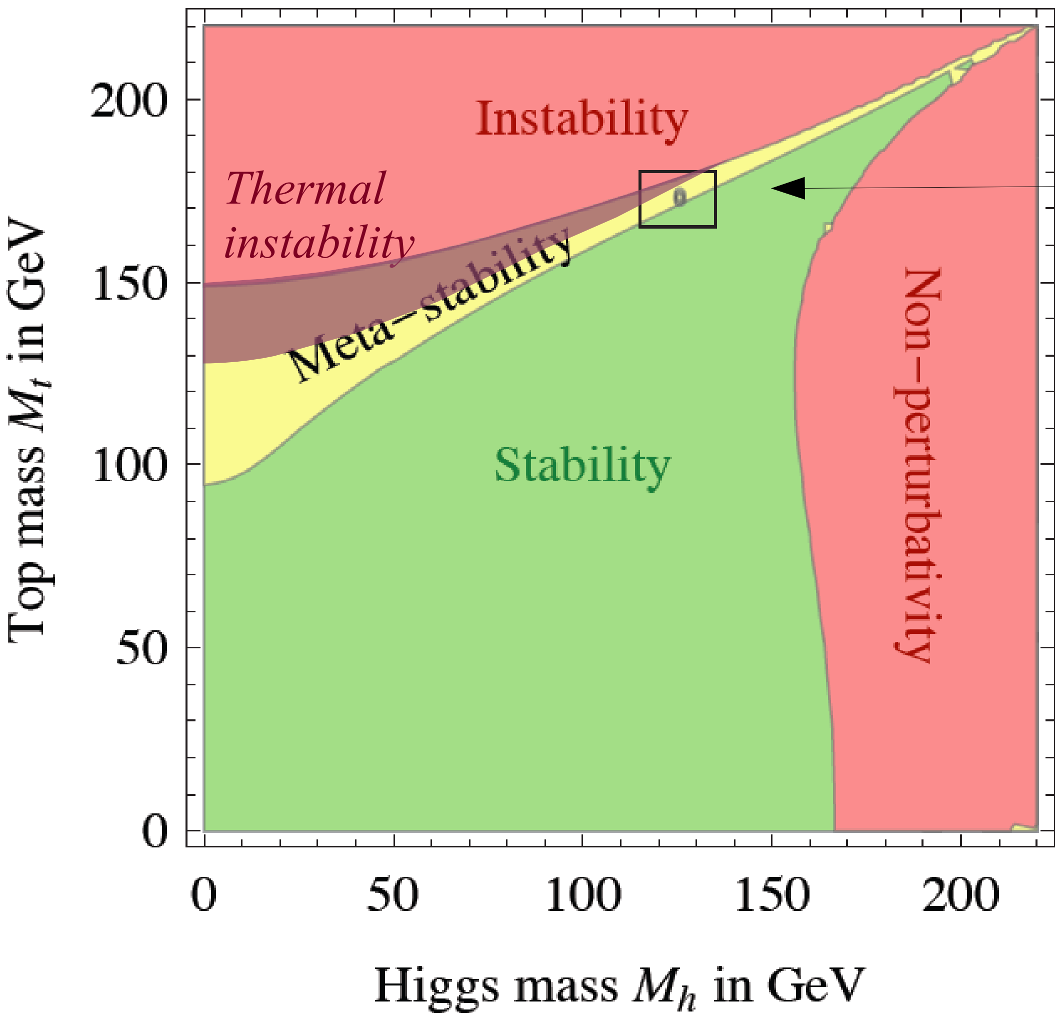
The error on m_h will soon go down → main uncertainty induced by the top mass.

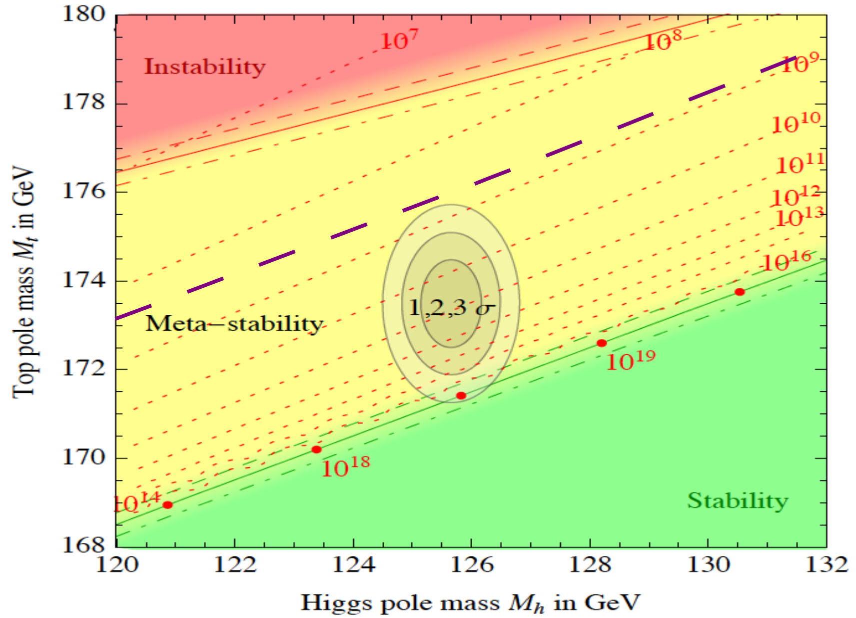
The m_t presently determined by ATLAS, CMS, Tevatron is not really the pole mass...

Hoang & Stewart, '07-'08
Alekhin, Djouadi, Moch '12,

… but nice convergence to the same m_t of several indep. measurements by ATLAS & CMS → small non-perturb. errors

The Higgs mass and the fate of the SM vacuum





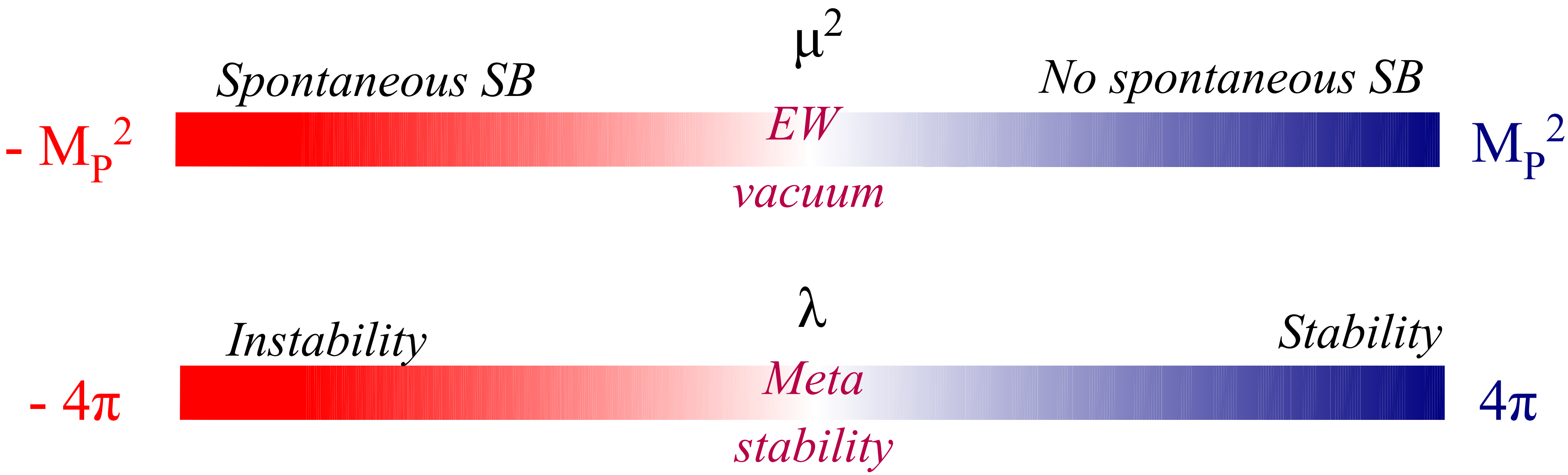
Froggatt, Nielsen, Takanishi, '01
Arkani-Hamed *et al.*, '08
Shaposhnikov, Wetterich, '10
+
many recent papers...

Looking at the plane from a more distant perspective, it appears more clearly that "we live" in a quite "peculiar" region...

The Higgs mass and the fate of the SM vacuum

It seems that the Higgs potential is "doubly tuned" around two "critical values":

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2$$



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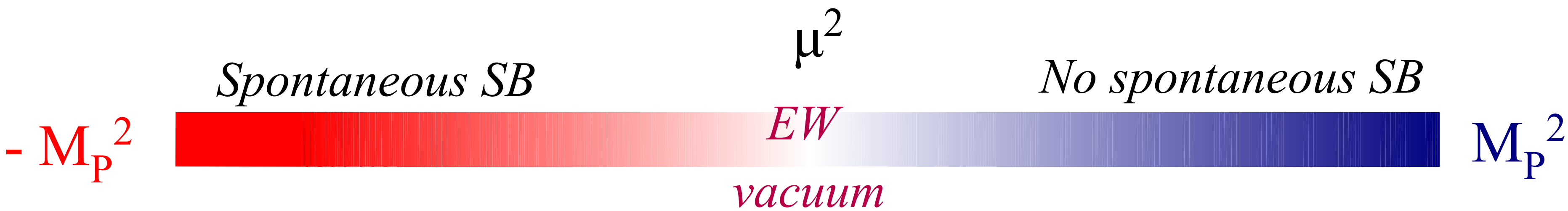
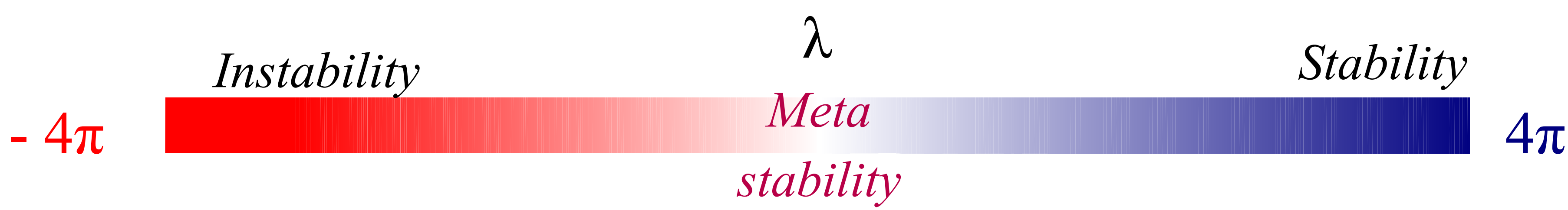




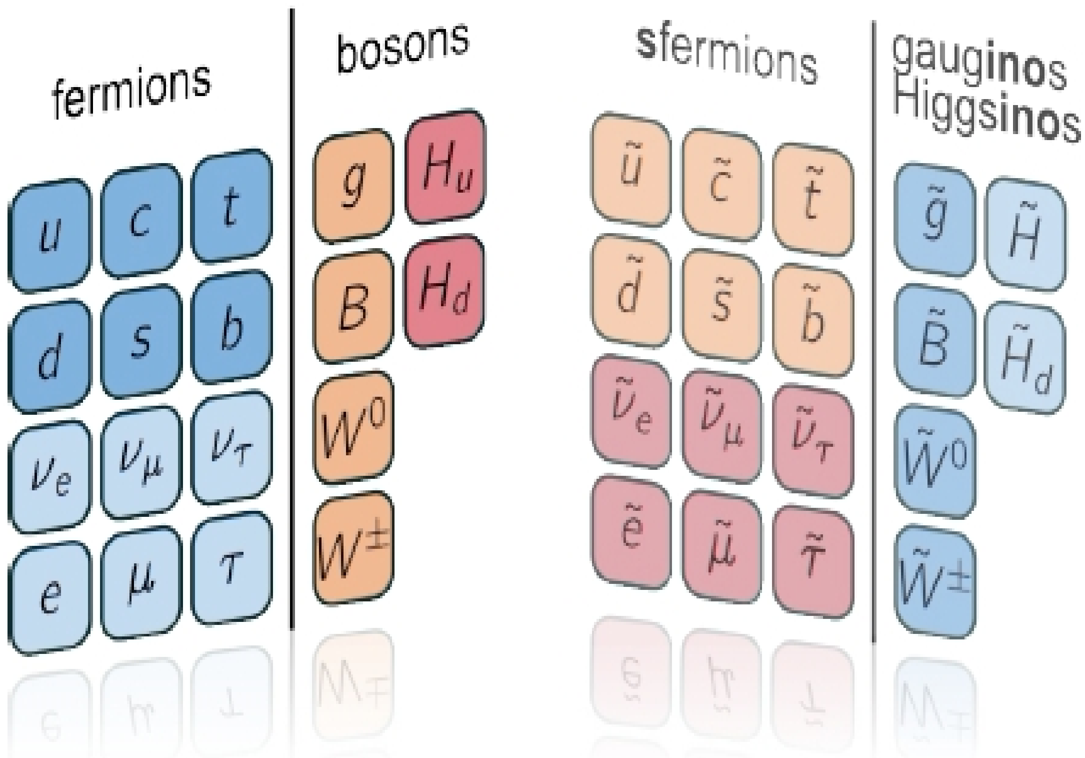
Close analogy with the cosmological constant [3rd critical parameter]

Is it an indication of some [*not completely understood yet*] statistical phenomenon occurring at high energies ["multiverse" + "anthropic selection"]...

…or it is nothing but a "coincidence"?

▶ Higgs and SUSY

A light Higgs is one of the key predictions of the MSSM...



Higgs and SUSY

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$$V^{tree}_{Higgs} = m_1^2 |H_U|^2 + m_2^2 |H_D|^2 + B^2 (H_D H_U + \text{h.c.})$$
$$+ \frac{1}{8}(g_1^2+g_2^2)(|H_U|^2-|H_D|^2)^2 + \frac{1}{2} g_2^2 |H_D H_U|^2$$

$\downarrow$

$$m_h^{tree} < |\cos(2\beta)|\, m_Z$$

Higgs and SUSY

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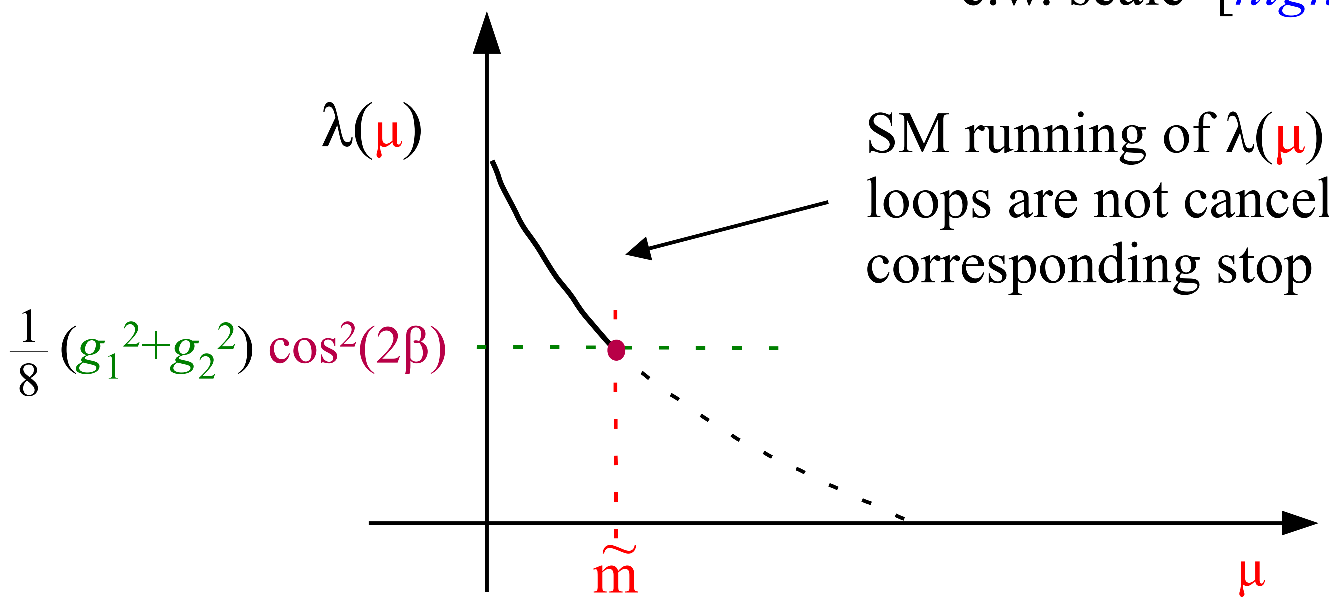
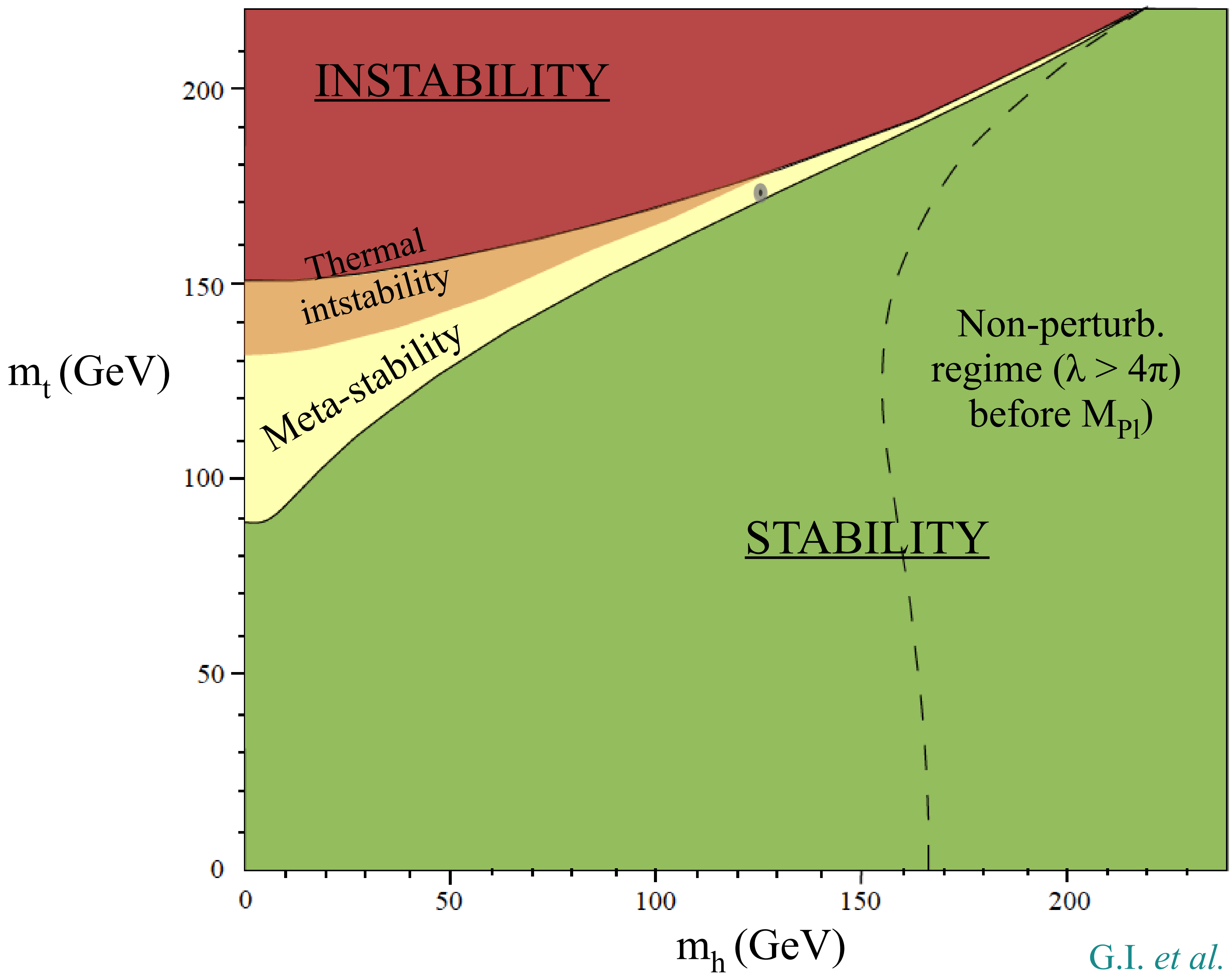
$$m_h^{tree} < |\cos(2\beta)|\, m_Z$$

This prediction is significantly modified if SUSY partners appear well above the e.w. scale [*high-scale*, *split*, *mini-split*...]



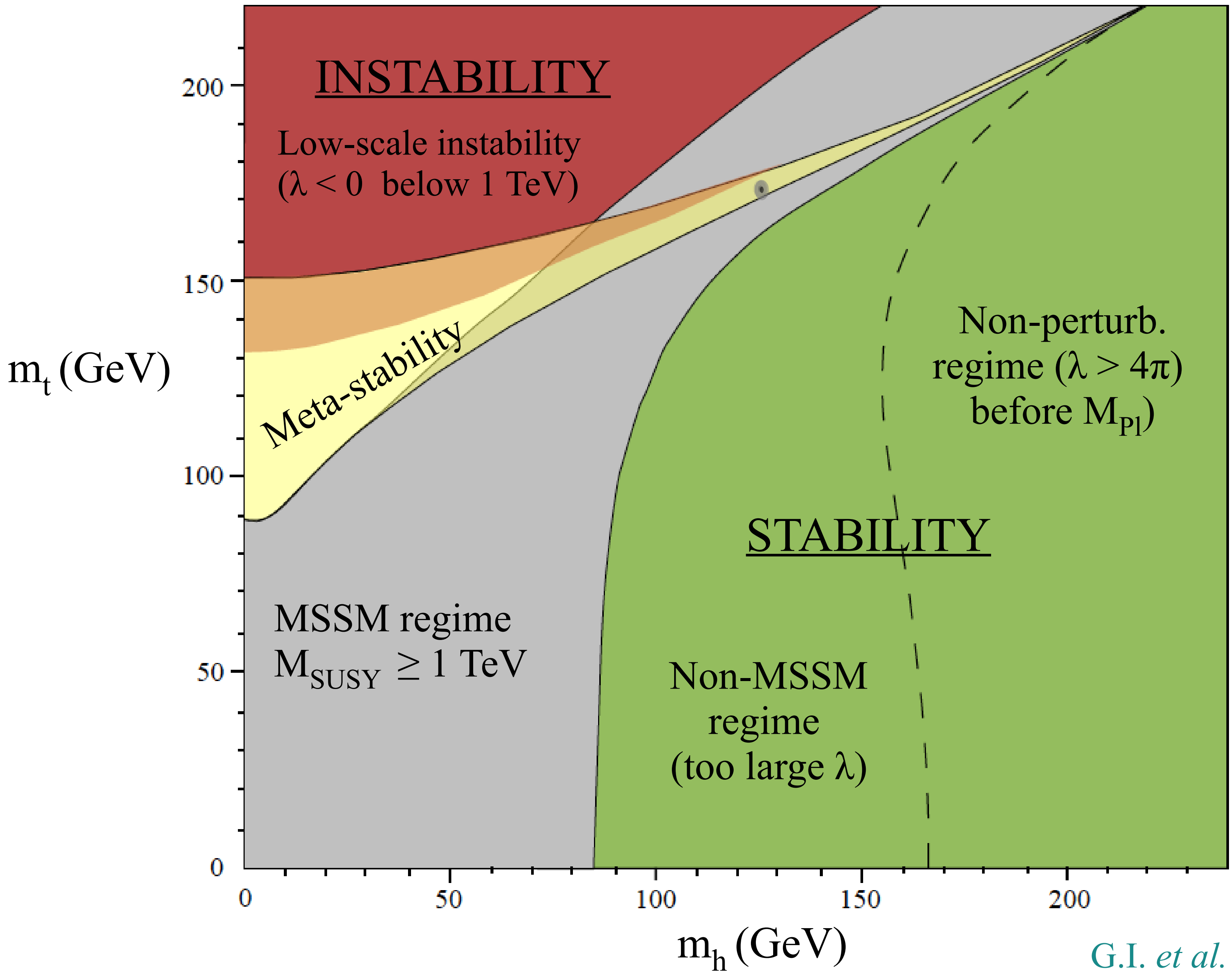
SM running of $\lambda(\mu)$ if top and Higgs loops are not canceled by corresponding stop and higgsino loops

Higgs and SUSY



G.I. *et al.* - work in prog.

Higgs and SUSY



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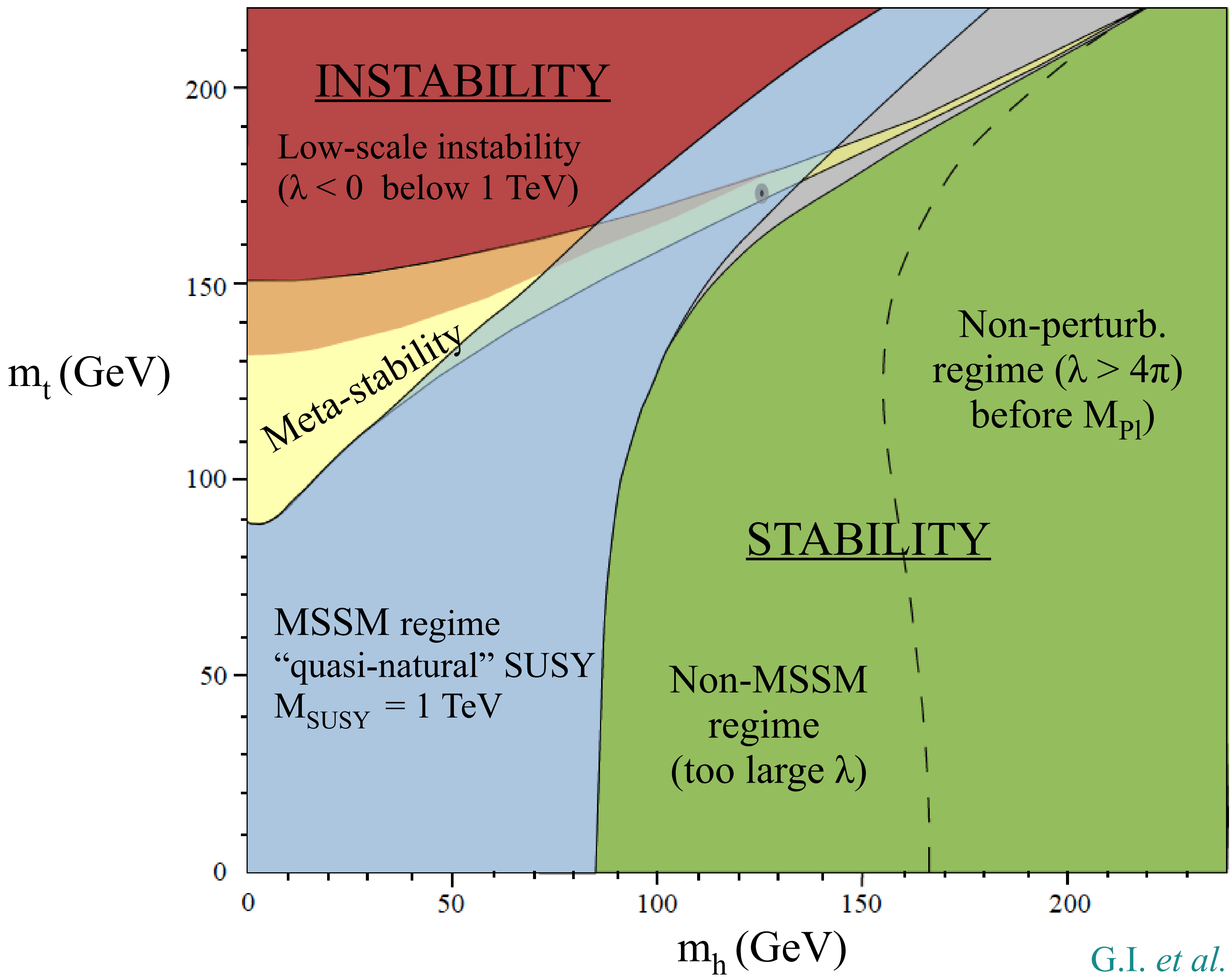
Higgs and SUSY



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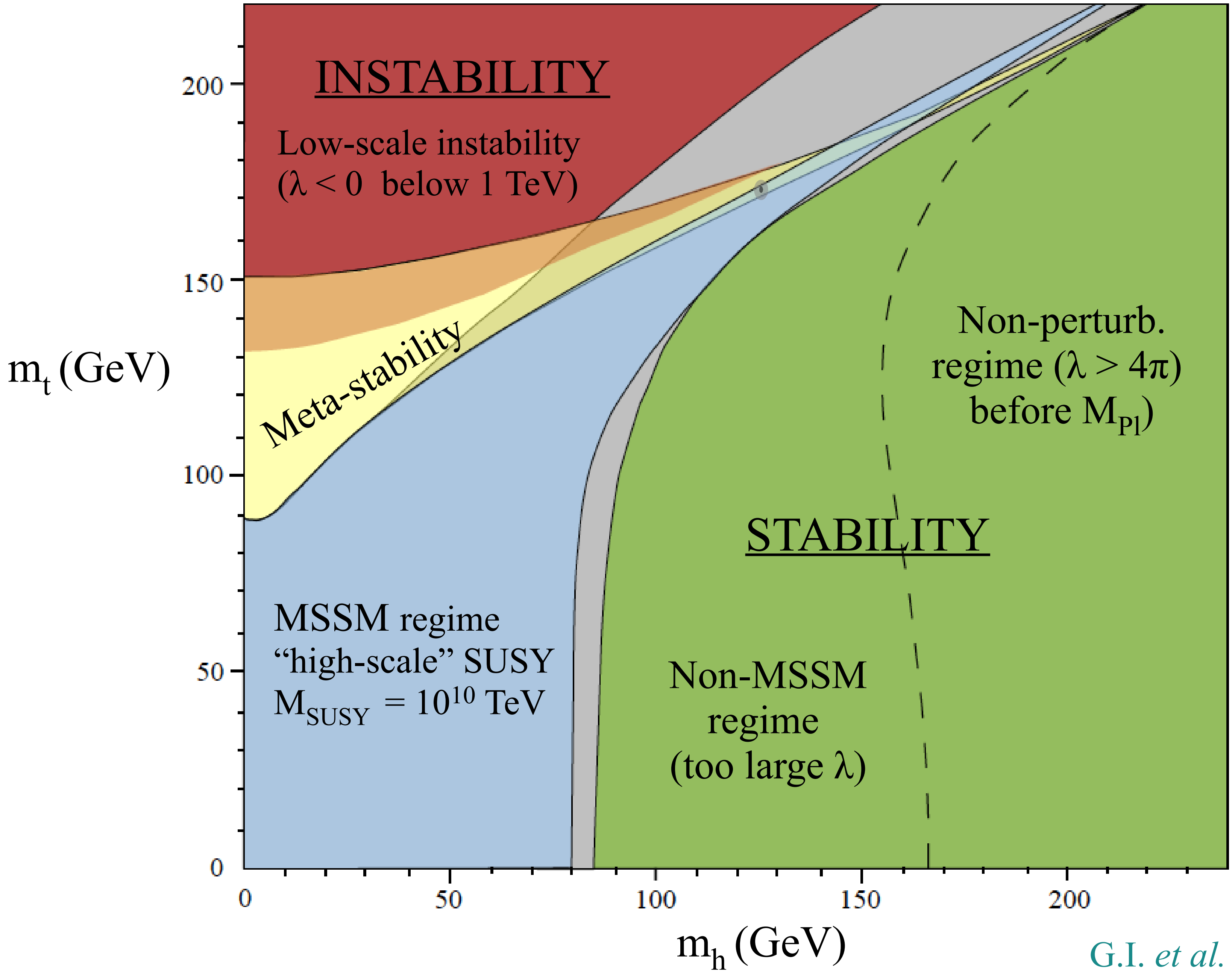
▶ Higgs and SUSY



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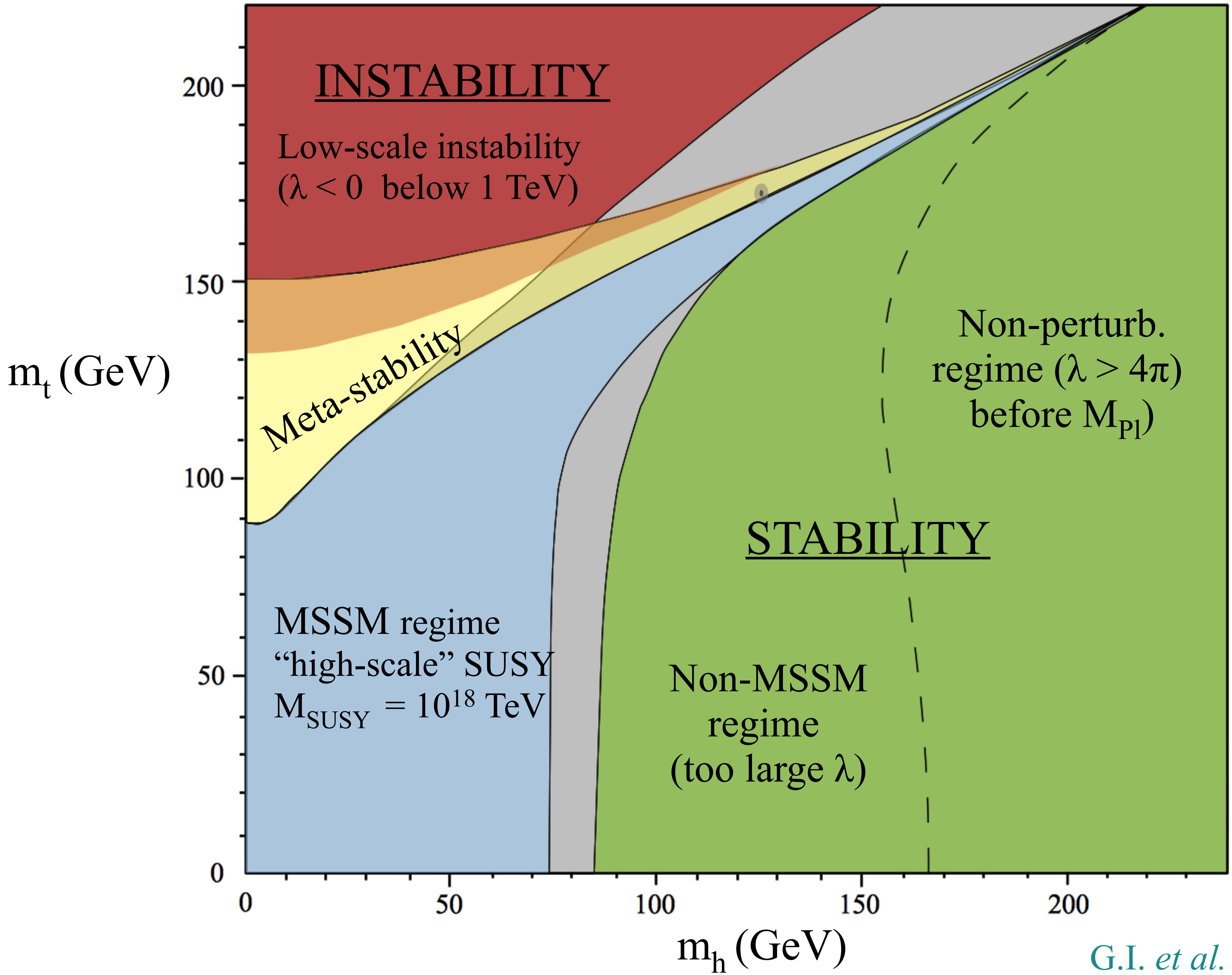
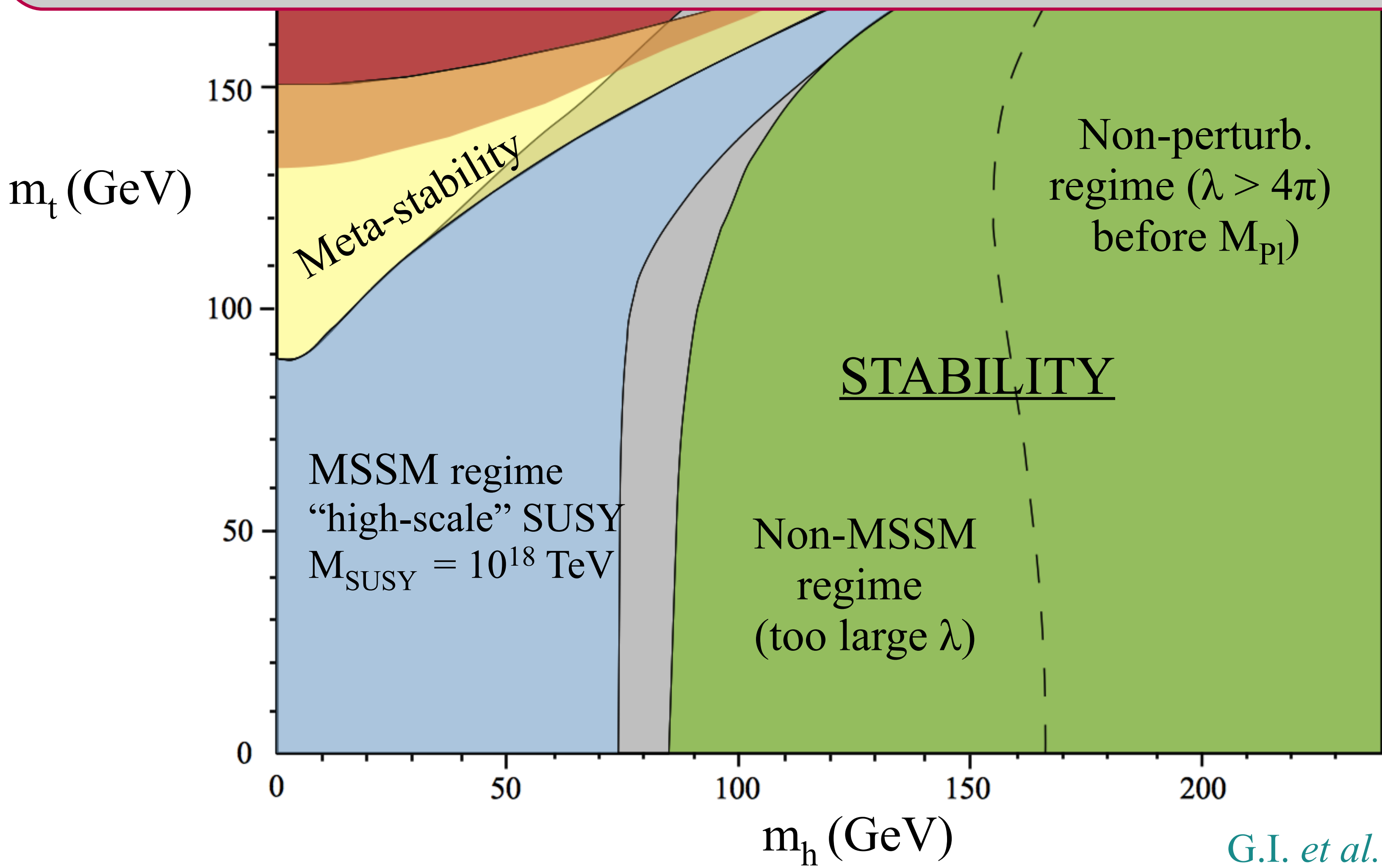
Higgs and SUSY



G.I. *et al.* - work in prog.

Higgs and SUSY

Message n.3: A light SM-like Higgs with m_h ≈ 125-126 GeV fits very well with SUSY, but it gives no clear clues about the SUSY breaking scale (beside excluding a too-light SUSY spectrum, in agreement with LHC findings)



G.I. *et al.* - work in prog.

What's next?

As usual, we have two complementary roads ahead of us

Direct searches

Indirect searches

What's next? Precision Higgs studies

As usual, we have two complementary roads ahead of us

Direct searches

not for today...

Indirect searches

Higgs Observables

What's next? Precision Higgs studies

The evidence of the new boson, compatible with the properties of the massive excitation of the Higgs field, indicates that the symmetry breaking sector of the effective theory has a *minimal* and *weakly coupled* structure...

$$\mathscr{L}_{\text{Symm. Break.}}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi) + \ldots$$

$$V(\phi) = - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\ i} \psi_R^{\ j} \phi$$

...but we are far from having established that there is nothing else beside the SM (*or that the cut-off of SM viewed as an effective theory is very high*)

⬇

On general grounds, it is natural to expect possible deviations from the SM in the Higgs sector

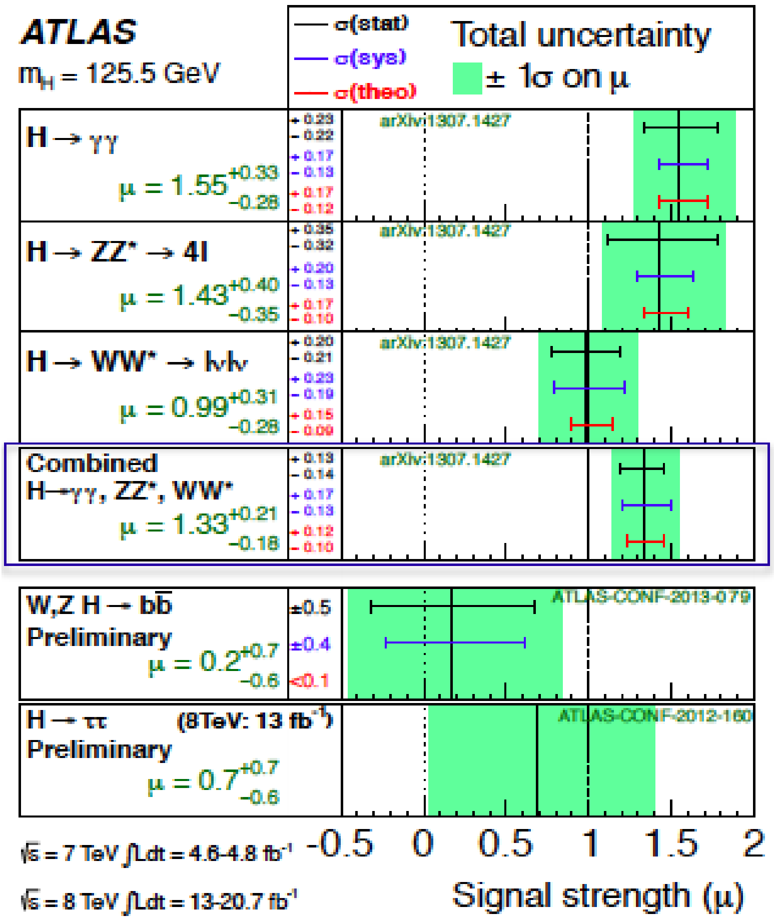
⬇

High-precision Higgs physics

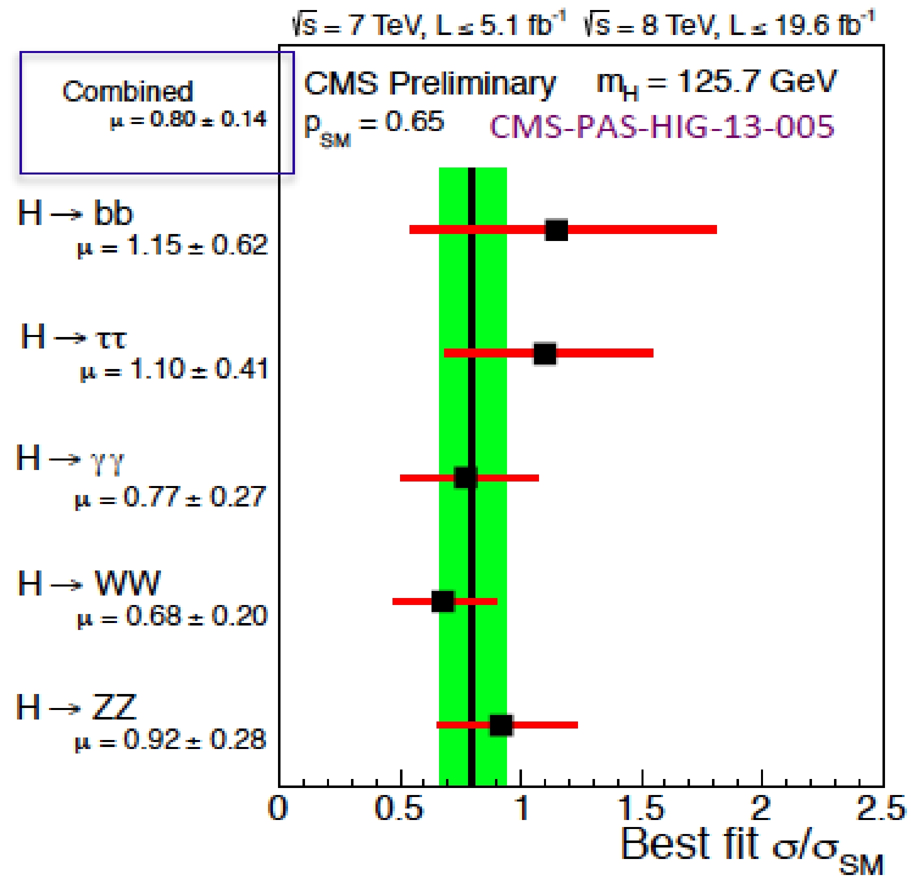
N.B.: the vast majority (and the less know) couplings of the Higgs field are couplings to the SM fermions

What's next? Precision Higgs studies

Several attempts in this direction have already started...



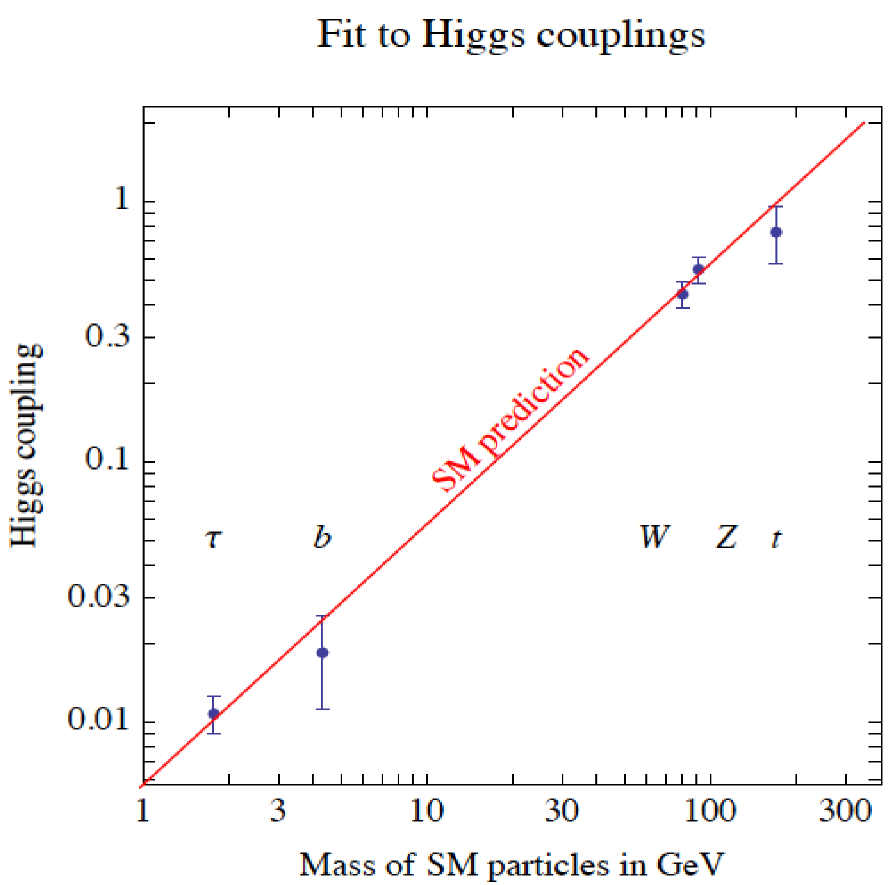
Phys. Lett. B 726 (2013), 88-119

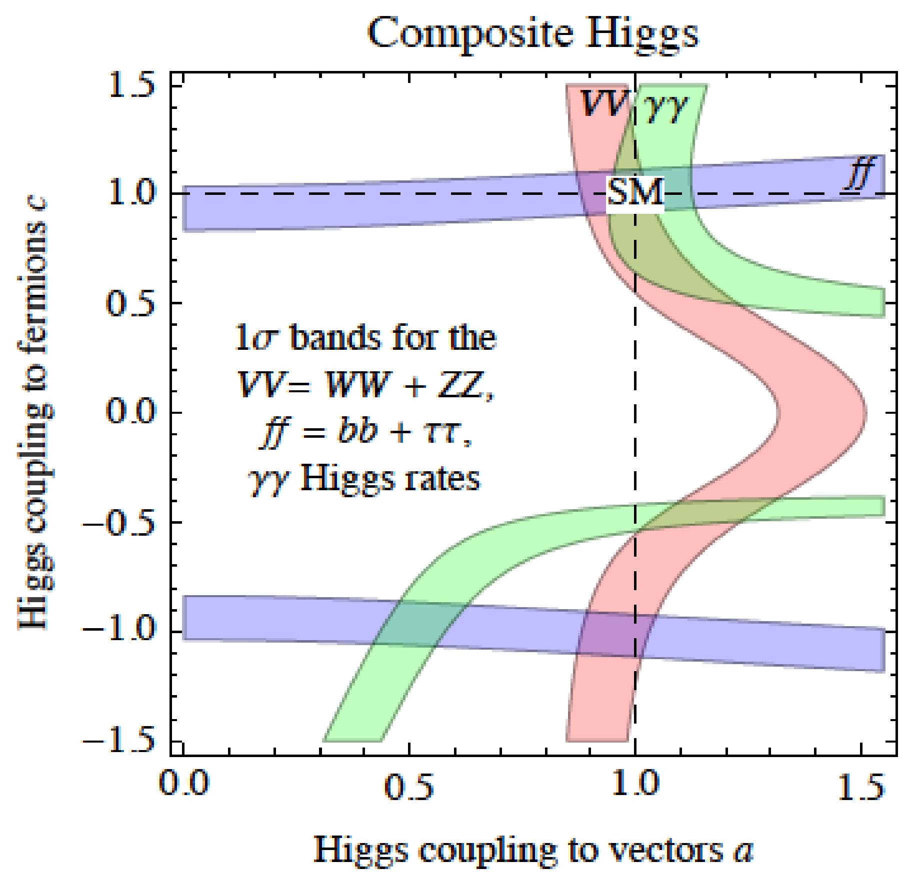


What's next? Precision Higgs studies

Several attempts in this direction have already started...

The study of the "signal strengths" in the 5 dominant modes [*and possible fits with reduced n. of parameters*] offers a good tool to test different extensions of the SM:





Giardino *et al.* '13 [similar results by many other groups]

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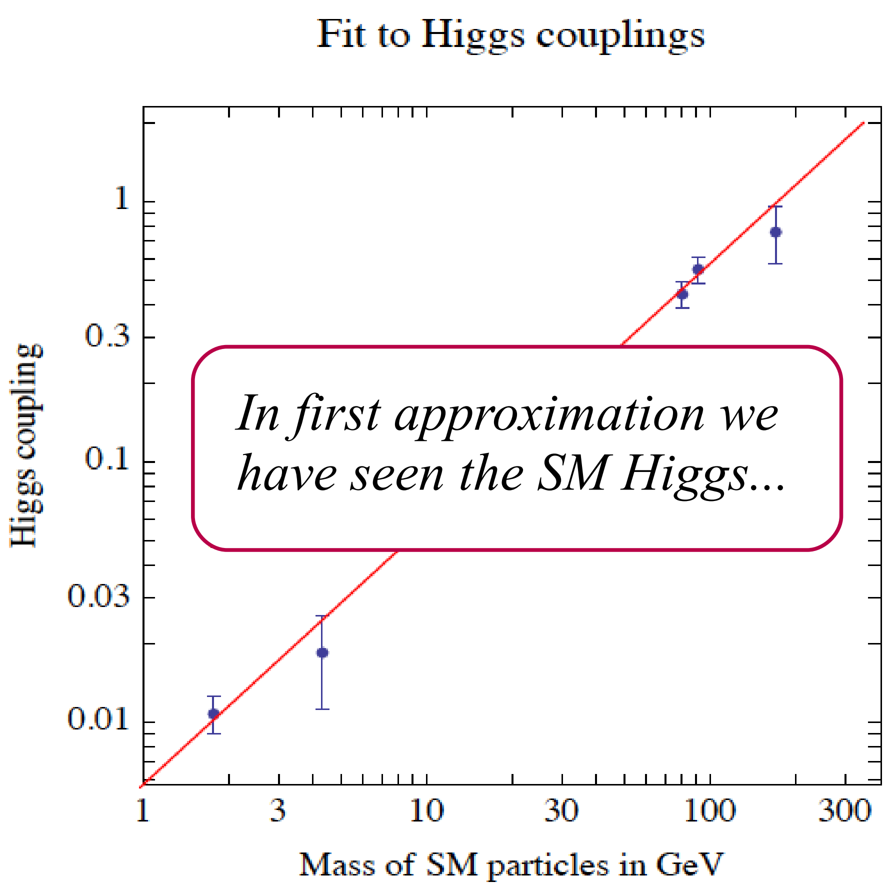
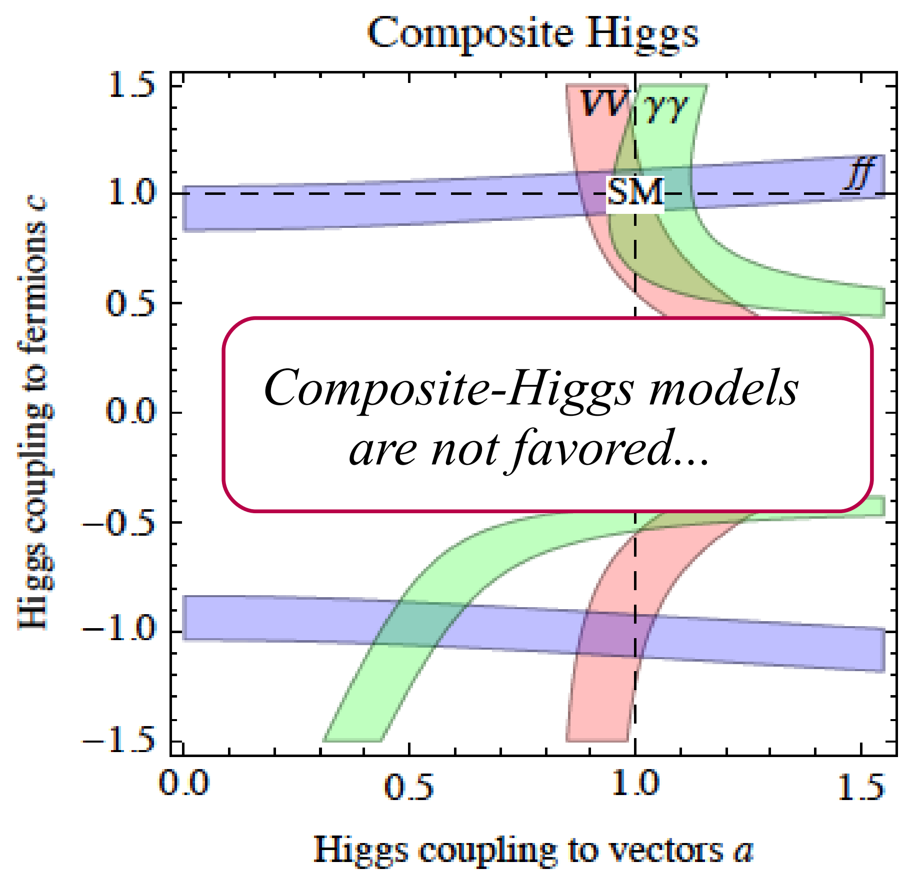




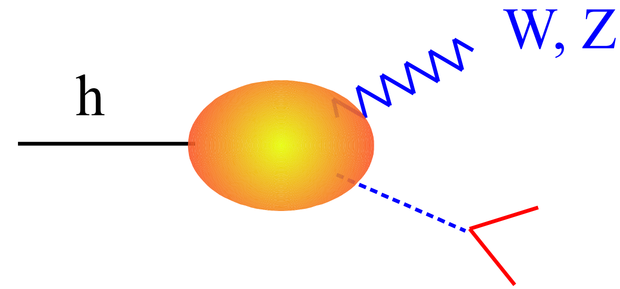
Giardino *et al.* '13 [similar results by many other groups]

What's next? Precision Higgs studies

…but the peculiar value of m_h offers many more interesting tests:

Three (almost) unexplored directions:

Kinematical studies
in $h \to 4l$ & in V+h associated production



$A(h \to Vff) \neq A(h \to VV^*)$

GI, Manohar, Trott, '13
Grinstein *et al.* '13, GI, Trott, '13

Rare SM modes
[including *exclusive semi-hadronic* decays]

E.g.:
$h \to Z\gamma$ [$BR_{SM} \sim 1.5 \times 10^{-3}$]
$h \to \mu\mu$ [$BR_{SM} \sim 2.2 \times 10^{-4}$]
$h \to Z\Upsilon$ [$BR_{SM} \sim 1.6 \times 10^{-5}$]

GI, Manohar, Trott, '13
Bodwin, Petriello, Sonyev, Velasco, '13

Exotic/forbidden decay modes
[e.g. *LFV* modes, *h → invisible*, *h → new light states*, ...]

E.g.:
$h \to \mu\tau$
$h \to Z+A$
…

Blankenburg, Ellis, G.I. '12
Harnik, Koop, Zupan, '12
Curtin *et al.* '13

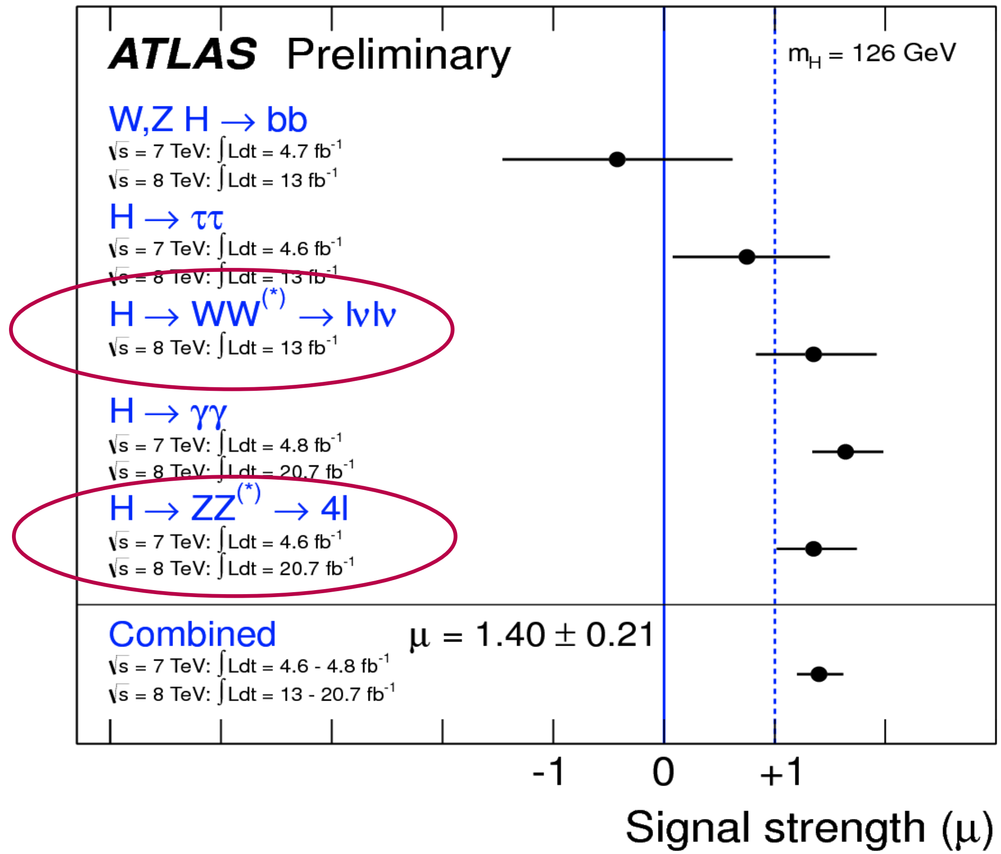
What's next? Precision Higgs studies [I. Kinematical studies]

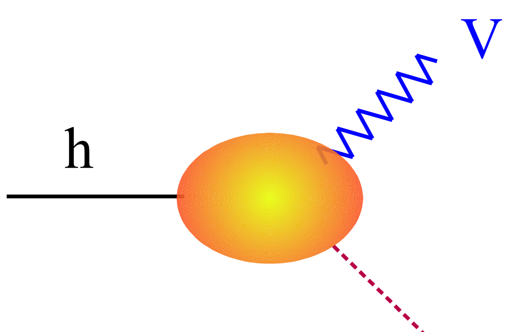
ATLAS and CMS have reported results about the $h \to WW^*$ & $h \to ZZ^*$ couplings

However, what is really measured are 4-lepton modes.

With suitable cuts what can be probed in experiments is the $h \to Vff$ amplitude (V=W, Z) and, in general,

$$A(h \to Vff) \neq A(h \to VV^*)$$





$$J_\mu^f = \bar{f}\,\gamma_\mu (v^f + a^f \gamma_5)\, f$$

▶ *What's next? Precision Higgs studies* [I. Kinematical studies]

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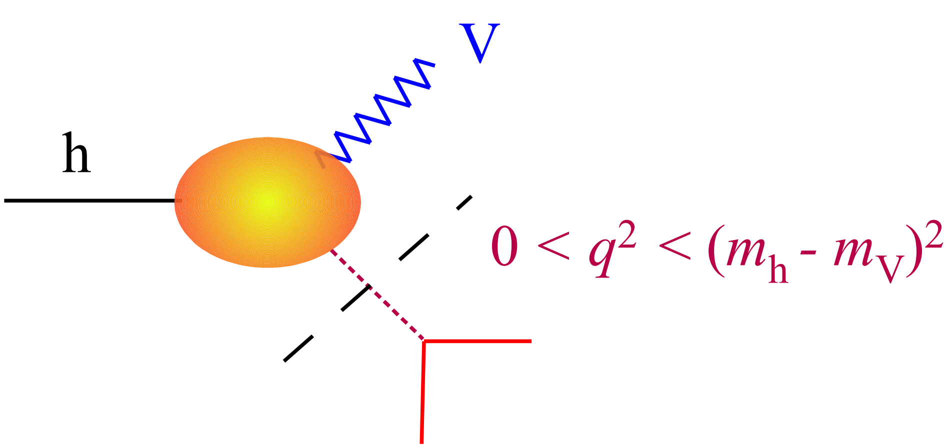


The "offshellness" of the second lepton pair allows to probe a richer dynamical structure:

- We are far enough from the pole of the amplitude at $q^2 = m_V^2$ (*the only pole within the SM*)
- Measuring the q^2 dependence we could reveal new "distant poles" (↔ *contact interactions*) or even new "light poles" (↔ *new light states coupled to h & fermions*)
- General parametrization in terms of four $hVff$ form-factors

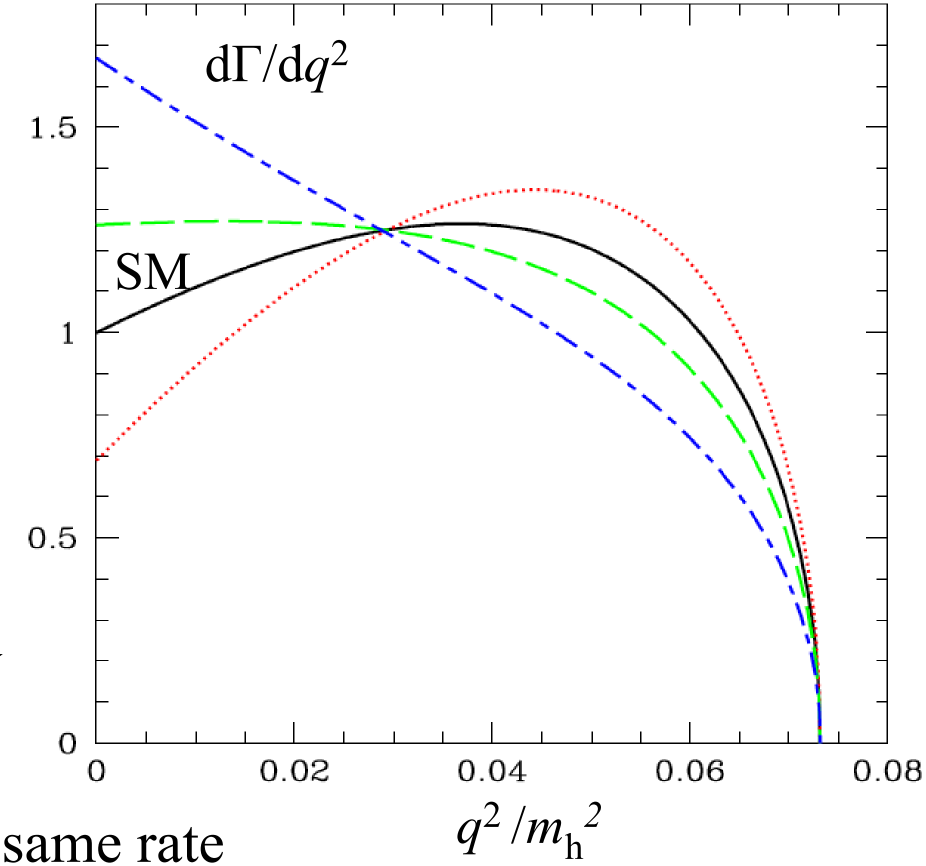
GI, Manohar, Trott, '13

What's next? Precision Higgs studies [I. Kinematical studies]

So far the $h \to 4l$ analysis were focused on determining

- The signal strength (= total rate)
- The J^{CP} properties of h

However, we know very little yet about possible modification of the $q^2 = m_{ll}^2$ spectrum, that can easily occur even if h is a 0^+ state



Possible modifications of the spectrum,
With generic NP ~ few TeV, leading to the same rate

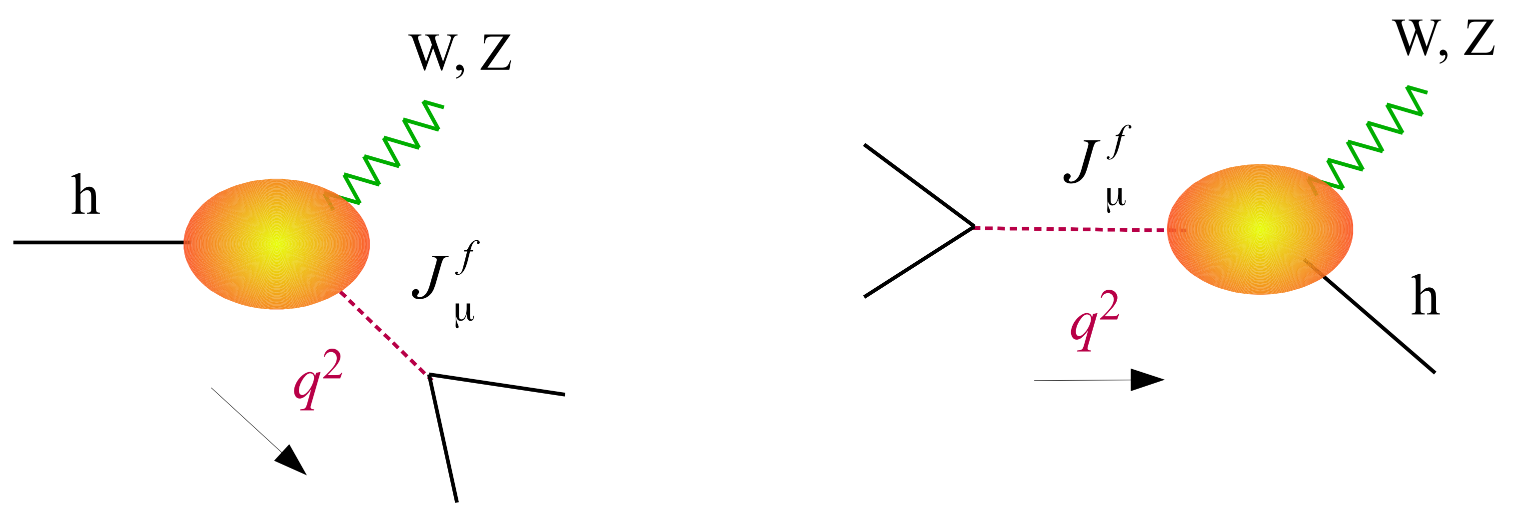
→ significant constraints from EPWO [Ciuchini *et al*.; Pomarol & Riva, '13]

However...
- significant deviations in the *Zll* spectrum still possible [Max Carrel, '13]
- testing if such constraints are verified is a powerful tool to test if h is indeed part of an SU(2) doublet

GI & Trott, '13

What's next? Precision Higgs studies [I. Kinematical studies]

The *hVff* form *f*actors are accessible also inV+h associated production in a different kinematical regime



$0 < q^2 < (m_h - m_V)^2$ $q^2 > (m_h + m_V)^2$

Of course the *f.f.* probed in associated production at LHC maybe different from those appearing in h → *Zll,* in case of flavor-non-universal contact interactions.

What's next? Precision Higgs studies [II. Rare Higgs decays]

On general grounds, rare/exotic Higgs decays offer a very interesting window to NP

On the TH side:

- Unique window on models where (light) NP couples directly (*effective tree-level coupling*) only to the Higgs field (*Higgs portal*, …)
- Large deviations from the SM less constrained by other observables (e.g. EWPO)

Curtin *et al.* '13

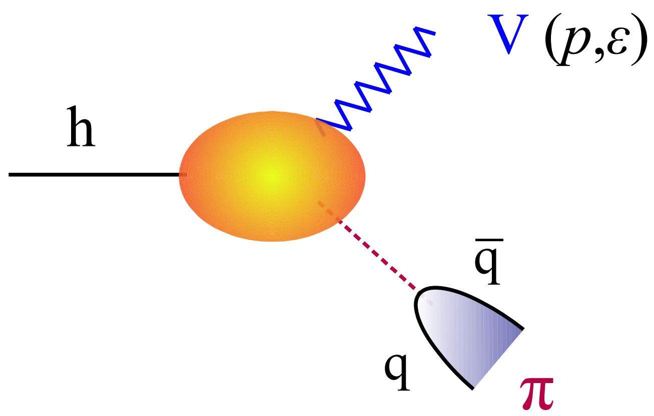
On the EXP side:

- Hopefully more room for improvement with increasing statistics vs. the (slow) improvement in measurements where we have already seen the SM signal...

What's next? Precision Higgs studies [II. Rare Higgs decays]

The exclusive hadronic/semi-hadronic decays:

Rare $h \to V+P$ decays, where P is a single hadron state (*pseudo-scalar* or *vector-meson*) are a very interesting probe of the vacuum-structure of the theory



$$A^{SM} \propto \frac{f_P}{v}$$

ratio of the two order parameters controlling the $SU(2)_L$ *breaking*

GI, Manohar, Trott, '13

What's next? Precision Higgs studies [II. Rare Higgs decays]

The exclusive hadronic/semi-hadronic decays:

The SM rates are suppressed but not outrageously small (*thanks to* m_h ~125 GeV), and some channels may have a (*relatively*...) clean signature

VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.7×10^{-6}
$h \to \gamma J/\psi$	2.5×10^{-6}	$h \to Z\Upsilon$	1.6×10^{-5}

Sizable modifications possible in various BSM frameworks

GI, Manohar, Trott, '13

Bodwin, Petriello, Sonyev, Velasco, '13

GI & Gonzales-Alonso [work in prog.]

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Sizable modifications possible in various BSM frameworks

GI, Manohar, Trott, '13

$\rightarrow$ $BR[\, h \to W^{\pm} D_s^{\mp}(\gamma)\,] \approx 10^{-4}$

They definitely deserve a dedicated experimental search !

Conclusions

- A SM-like Higgs with m_h =125-126 GeV does not allow us to derive model-independent conclusions about the scale of New Physics: the SM Higgs potential is unstable but sufficiently long-lived.

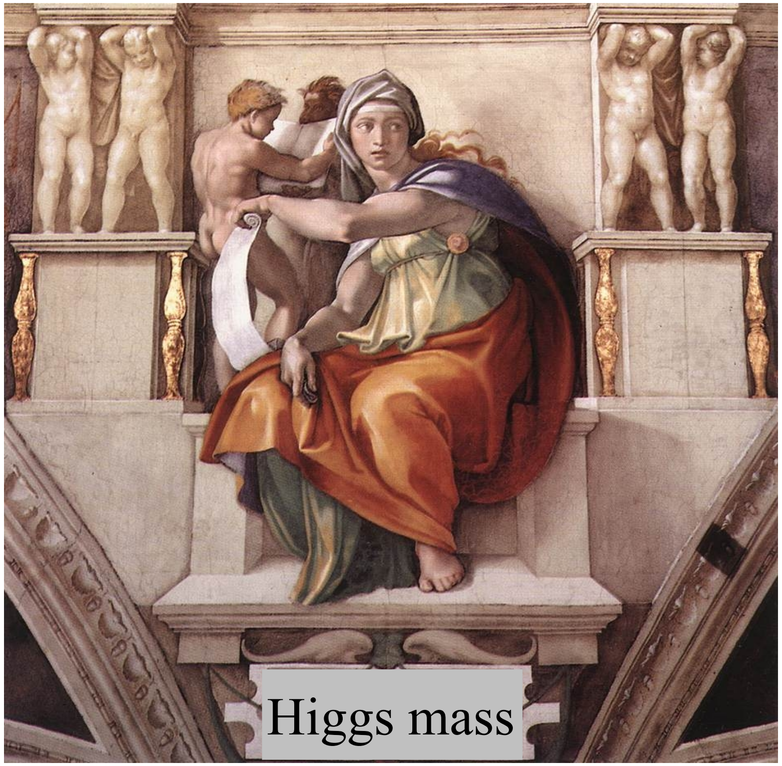
- Clear indication of a small λ at high energies: SUSY remains an excellent candidate as UV completion of the SM, but m_h alone leaves open a wide range of values for the SUSY breaking scale.

- The peculiar "doubly-critical" structure of the Higgs potential may be the indication some (*non-completely understood yet*) statistical phenomenon, (→ "Multiverse" ?)

- *Leaving aside theoretical prejudices*... there is still a lot to learn about Higgs physics: differential distributions and rare decays (not only those discussed in this talk) are almost unexplored windows that is worth to investigate in more detail.

Conclusions

My understanding of the "Higgs-mass oracle":



" SM valid up to high scales No SUSY will show at LHC13 "

Conclusions

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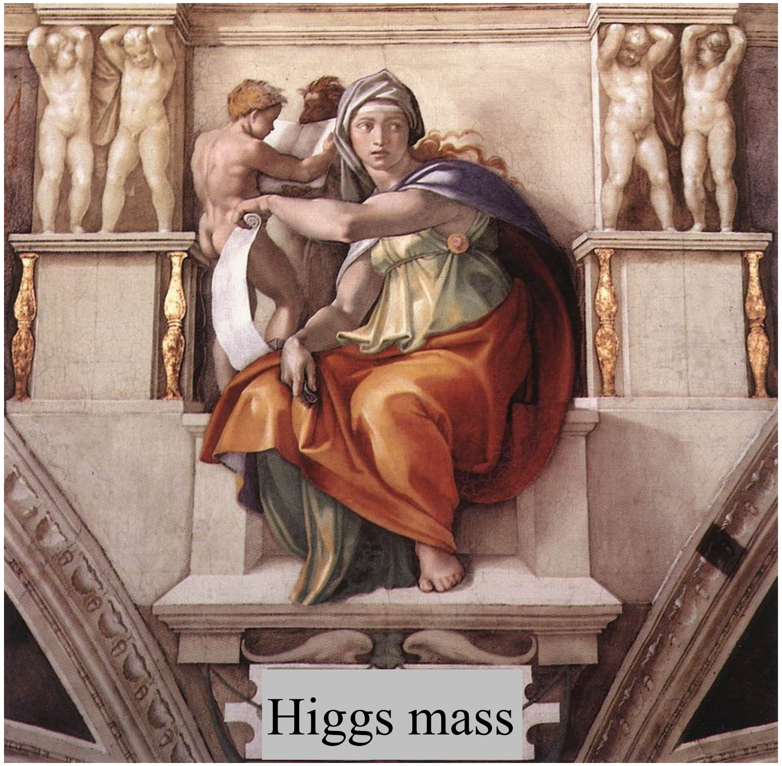


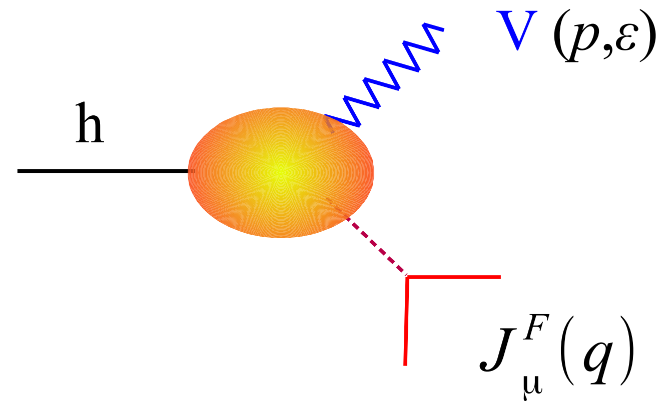
" SM valid up to high scales No SUSY will show at LHC13 "

SM valid up to high scales.
No SUSY will show at LHC13.

SM valid up to high scales?
No: SUSY will show at LHC13!


Backup

▶ Kinematical studies [mainly h → 4*l*]



Assuming J(h)= 0 → general decomposition of the amplitude in terms of *4 independent form factors*:

$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} \left[f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu + f_3^V(q^2)(p\cdot q\, g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2)\epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

GI, Manohar, Trott, '13

- SM limit: $f_1 = 1$, $f_2 = -1/m_V^2$, $f_{3,4} = 0$
- f_2 do not contribute to conserved currents (→ irrelevant for *l*=e,μ)
- f_3 do not contribute if $J_\mu \sim q_\mu$
- Re(f_4) is CP odd in h → ZZ* if CP(h)=+
- Im(f_4) is CP even, but it is allowed only for a hW*lv* local interaction

▶ *Kinematical studies* [mainly $h \to 4l$]

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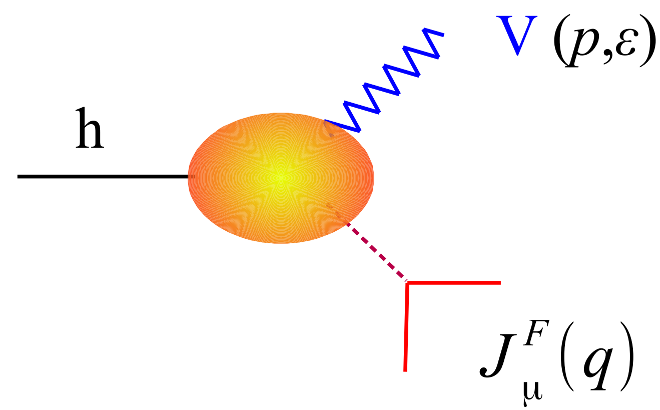

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N.B.: This structure is more general than what presently used to analyze data:

$$\mathcal{A}_{VV*} = \frac{\kappa}{(q^2 - m_V^2)} \left[a_1\ g^{\mu\nu} + a_2\ q^\mu p^\nu + a_3\ \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma \right]$$

KEY POINT:

$a_i \to a_i(q^2)$

…but is trivial to relate the two parameterizations for $h \to Z+ll$

$a_1(t) = f_1(t) + f_3(t)\times(m_h^2 - m_V^2 - t)/2$ $a_3(t) = -f_3(t)$ $a_4(t) = f_4(t)$

Kinematical studies [mainly $h \to 4l$]

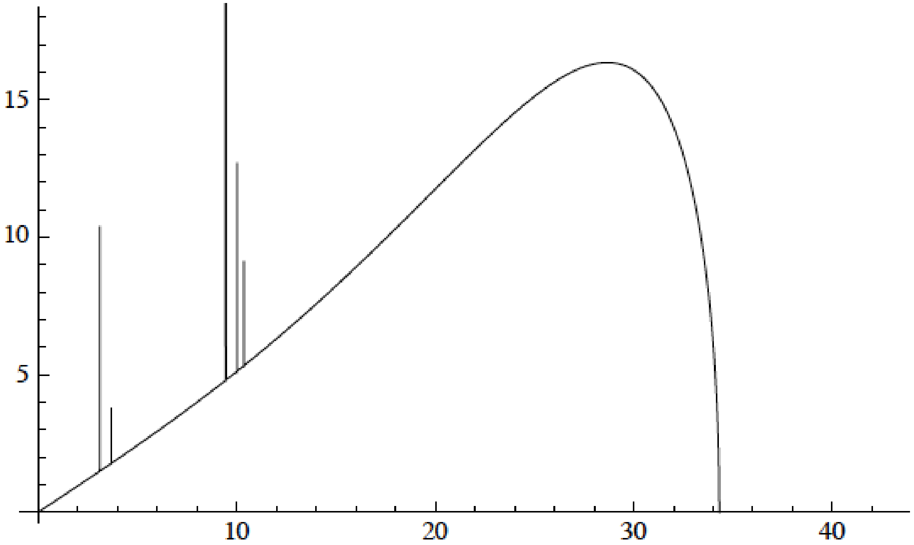
The (spin-averaged) double differential distribution is the most efficient way to perform a model-indep. analysis aimed to extract the CP-conserving $f_i\,(q^2)$

$$\frac{d^2\Gamma}{d\,m_{34}\,d\cos\theta}$$

Possible to derive a very precise SM distribution, even at low m_{34}, including charmonium states [GI & Gonzales-Alonso, work in prog.]:

$d\Gamma/dm_{34}$

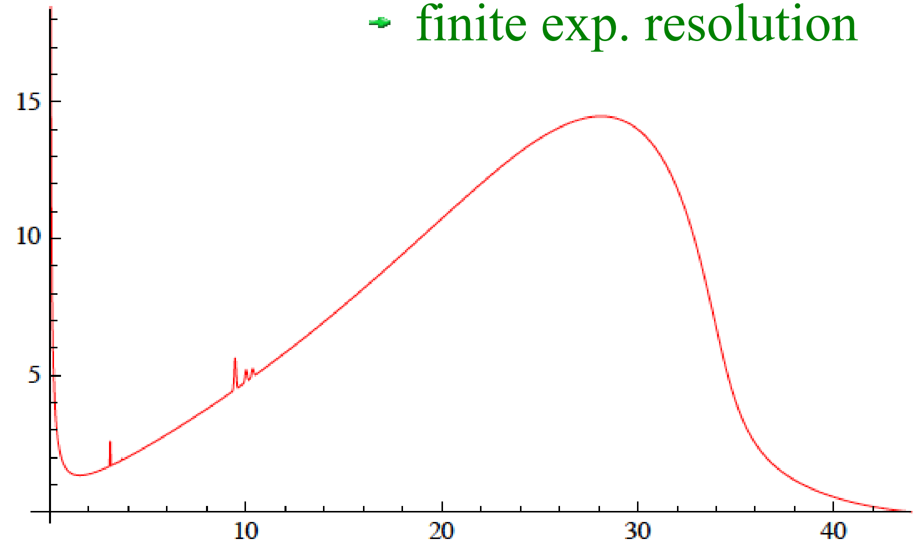
- no e.m. rad.
- on-shell Z



m_{34} [GeV]

$d\Gamma/dm_{34}$

- e.m. rad.
- off-shell Z
- finite exp. resolution



m_{34} [GeV]