About the Higgs boson

(On June 2012)

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Il modello di Higgs del Modello Standard

$$\phi^T = (\phi_1(x), \phi_2(x), \phi_3(x), \phi_4(x)) \qquad x = (\mathbf{x}, t)$$

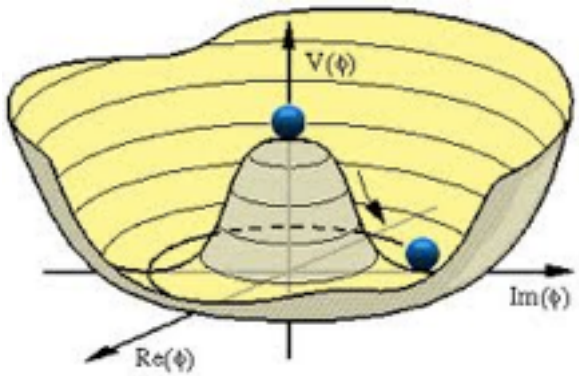
$$W^{\pm}, Z$$

$$\mathcal{E} = \frac{1}{2}\Sigma_i[(\frac{d\phi_i}{dt})^2 + (\nabla\phi_i)^2] + V(\phi)$$

$$V(\phi) = -\mu^2|\phi|^2 + \frac{\lambda}{2}(|\phi|^2)^2$$

$$|\phi|^2 = \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2$$

$$\phi \rightarrow R^{(4)}\phi$$



Soluzioni di minima energia:

$$< \phi_i >= \phi_i^0 \qquad | < \phi > |^2 = \Sigma_i(\phi_i^0)^2 = v^2 = \frac{\mu^2}{\lambda}$$

1 - Esiste una simmetria residua $R^{(3)}$ intatta: la simmetria dell'elettromagnetismo e' intatta $\Rightarrow$ la carica elettrica e' conservata

2 - La degenerazione del "vuoto" e' descritta da 3 angoli θ_i (6-3)

3 - Delle 4 particelle che corrispondono alle vibrazioni quantistiche del campo ϕ, tre (i θ_i) "spariscono" dallo spettro, mentre la quarta, il bosone di Higgs ha massa $m_h = \lambda v$

Rottura spontanea della simmetria ElettroDebole

$$\mathcal{L}^{(EWSB)} = |D_\mu \phi|^2 - V(\phi)$$

Interpretazione fisica: Una condensazione di BE di particelle scalari, che riempie tutto lo spazio in una configurazione costante, lo stato di minima energia del sistema

Conseguenze fisiche: $SU(2) \times U(1) \Rightarrow U(1)_{em}$

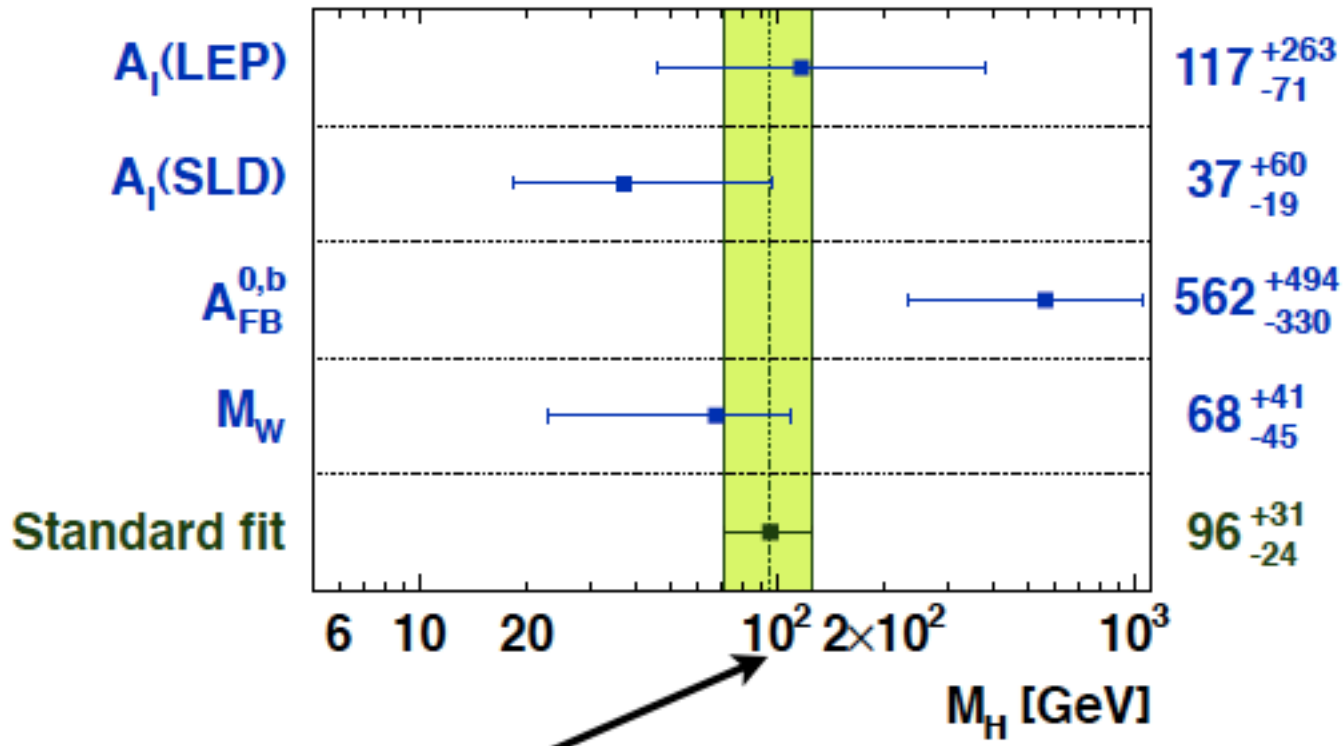
⇒ Viaggiando in questo mezzo, i "bosoni intermedi" e i fermioni acquistano massa

⇒ L'elettromagnetismo e le interazioni deboli sono distinti

⇒ Nel Modello "minimo", con 4 campi scalari per partire, esiste una particella scalare, il "bosone di Higgs", con accoppiamenti ai bosoni di gauge e ai fermioni determinati dalle masse rispettive

The Higgs boson mass in the SM

(una pagina di qualche tempo fa!)



$$M_{Higgs} = 96^{+31}_{-24}\ GeV$$

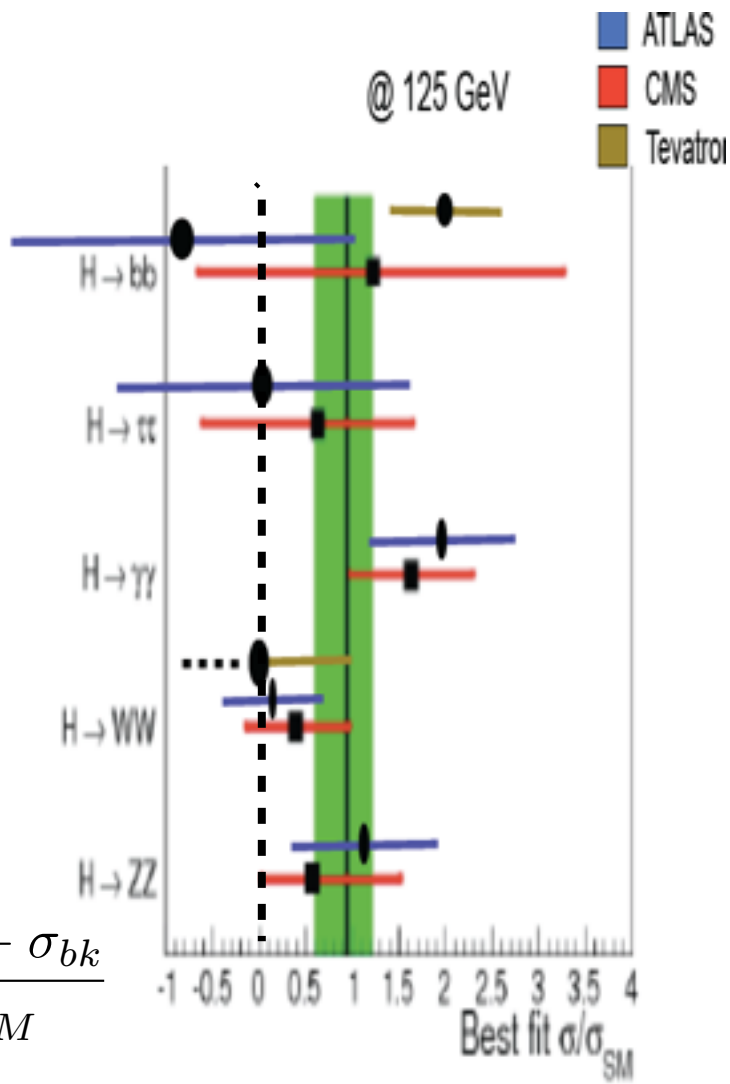
$$M_{Higgs} = 120^{+12}_{-5}\ GeV$$

with LEP and Tevatron direct searches included

Higgs boson searches after 2011

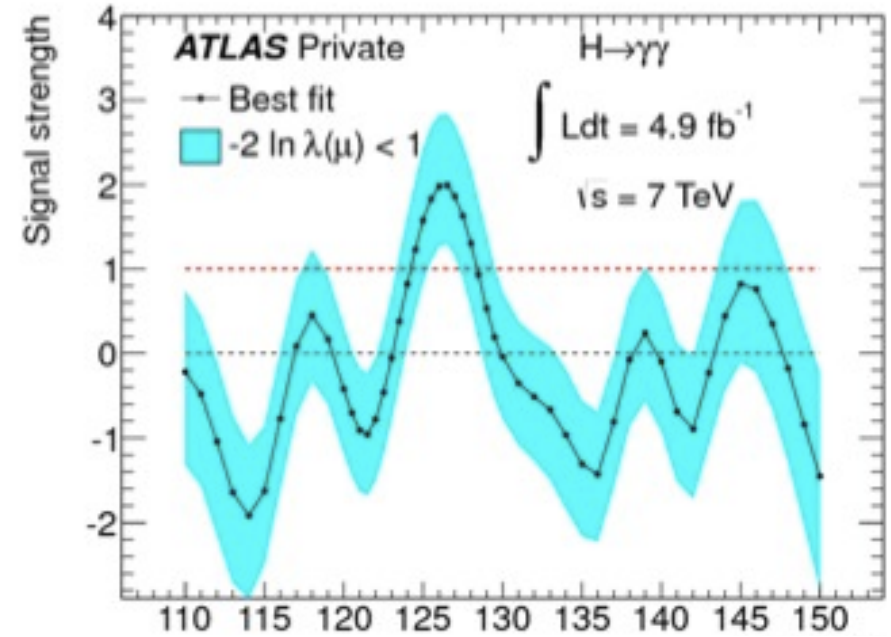
Let's be patient

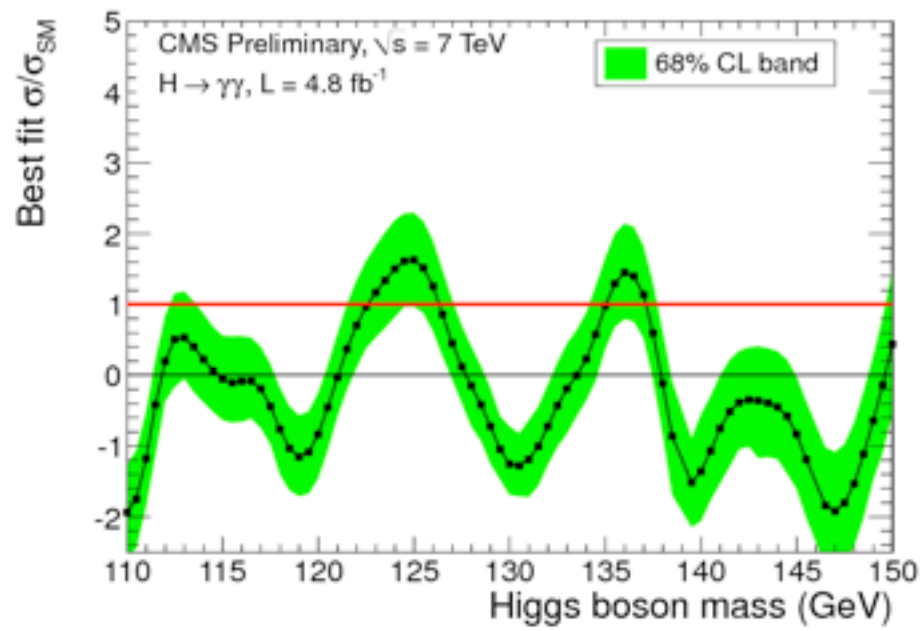
Yes, but....



$$\frac{\sigma_{obs} - \sigma_{bk}}{\sigma_{SM}}$$

(compiled by Gigi Rilandi)





As case study, accept "125 GeV discovery"

Standard/Non-standard Higgs couplings (at 125 GeV)

Tree Level

⇒ Not an elementary particle (other parameters for LHC14 only)

$$\mathcal{L} = a\left(\frac{2m_W^2}{v} W_\mu^+ W_\mu^- + \frac{m_Z^2}{v} Z_\mu^2\right)h + c^f \frac{m_f}{v} \bar{f} f h \qquad a_{SM} = c_{SM}^f \approx 1$$

⇒ mixing with other scalars

E.g.: $g_{hb\bar{b}}$ (↑↓ with SU(2) singlets, doublets or even triplets)

⇒ New missed final states

E.g.: $h \to \chi_{DM}\chi_{DM}$

Loop Level

⇒ with new virtual particles: $t, W;\ \tilde{t}, T, \rho_\mu^{\pm,0}, etc$

$$\mathcal{L}^{eff} = c^\gamma \frac{\alpha}{\pi v} F_{\mu\nu}^2 h + c^g \frac{\alpha_S}{12\pi v} G_{\mu\nu}^2 h \qquad c_{SM}^\gamma = 2/9,\ c_{SM}^g \approx 1$$

Can have large effects, δa/a, δc/c = O(1), if new physics nearby

Higgs widths

⇒ Relative to the SM, the Higgs widths scales get approximately modified as

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma_{SM}(h \to b\bar{b})} \simeq |c_b|^2$$

$$\frac{\Gamma(h \to WW^*)}{\Gamma_{SM}(h \to WW^*)} = \frac{\Gamma(h \to ZZ^*)}{\Gamma_{SM}(h \to ZZ^*)} \simeq |c_V|^2 \equiv |a|^2$$

$$\frac{\Gamma(h \to gg)}{\Gamma_{SM}(h \to gg)} \simeq |c_g|^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)} \simeq \left|\frac{\hat{c}_\gamma}{\hat{c}_{\gamma,SM}}\right|^2$$

where, taking into account the W loop

$$\hat{c}_\gamma \approx c_\gamma - c_V \qquad \hat{c}_{\gamma,SM} \approx -0.8$$

Higgs rates

⇒ For $m_h = 125\ GeV$ the total width scales as

$$\frac{\Gamma_{tot}}{\Gamma_{tot,\mathrm{SM}}} \approx 0.61 c_b^2 + 0.24 c_V^2 + 0.09 c_g^2 + 0.06 c_\tau^2 \equiv c_{tot}^2$$

and, as long as $h \to b\bar{b}$ dominates Higgs widths

$$R_{VV^*} \equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to ZZ^*)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to ZZ^*)} \simeq \left| \frac{c_g c_V}{c_{tot}} \right|^2 ,$$

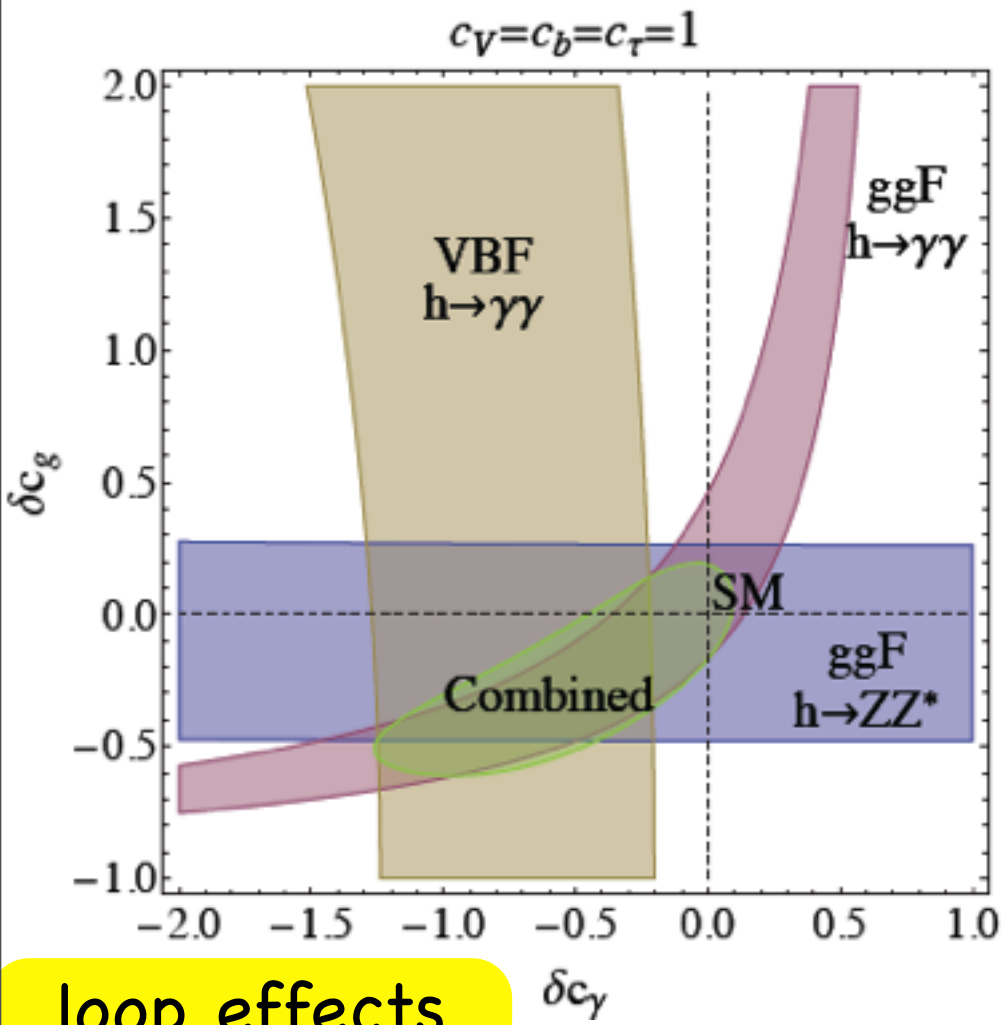
$$R_{\gamma\gamma} \equiv \frac{\sigma(pp \to h)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to h)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left| \frac{c_g \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_{tot}} \right|^2 ,$$

$$R_{\gamma\gamma}^{VBF} \equiv \frac{\sigma(pp \to hjj)\mathrm{Br}(h \to \gamma\gamma)}{\sigma_{SM}(pp \to hjj)\mathrm{Br}_{SM}(h \to \gamma\gamma)} \simeq \left| \frac{c_V \hat{c}_\gamma}{\hat{c}_{\gamma,SM} c_b} \right|^2 .$$

$$R_{b\bar{b}}^{\mathrm{Tev}} \equiv \frac{\sigma(p\bar{p} \to Vh)\mathrm{Br}(h \to b\bar{b})}{\sigma_{SM}(p\bar{p} \to Vh)\mathrm{Br}_{SM}(h \to b\bar{b})} \simeq \left| \frac{c_V^2 c_b^2}{c_{tot}^2} \right| ,$$

Examples of preparatory gymnastics (at 125 GeV)

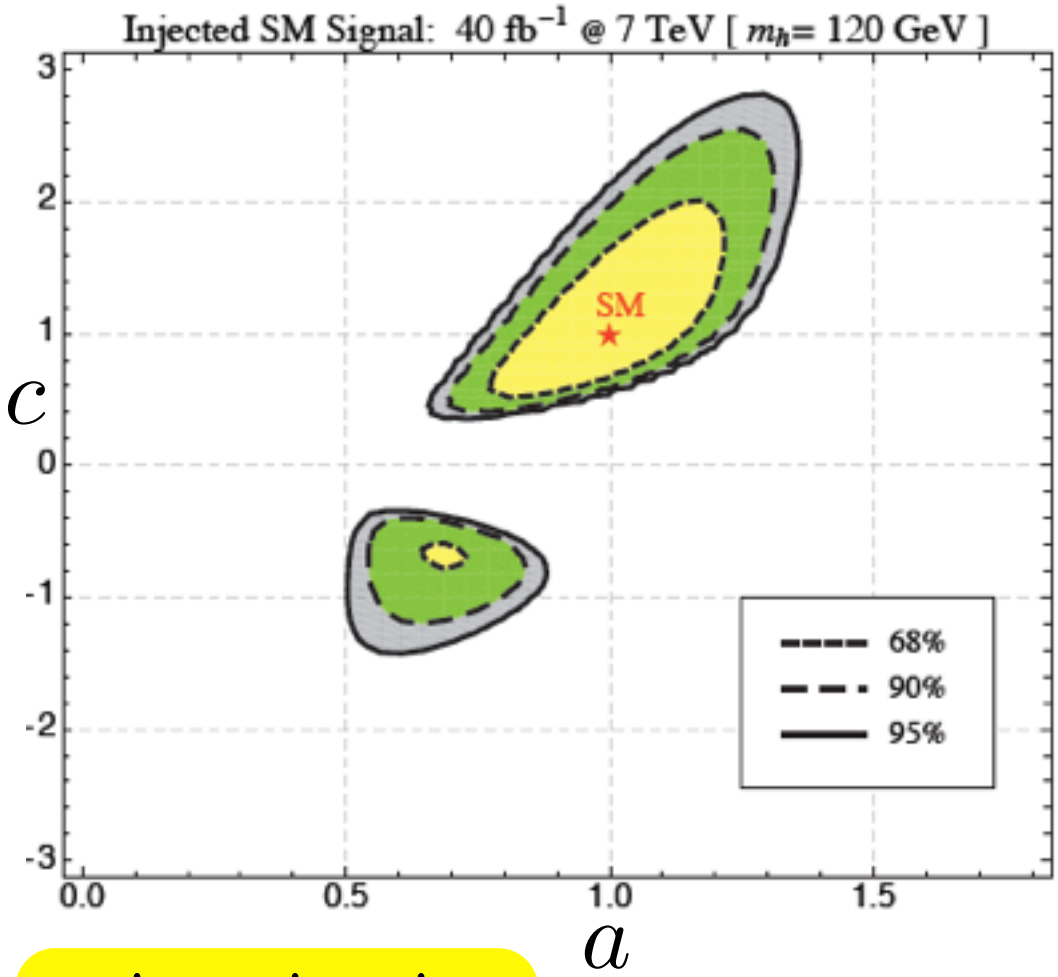
full 2011 data



loop effects

Carmi, Falkowski, Kuflik, Volansky

end of 2012 projection



tree level

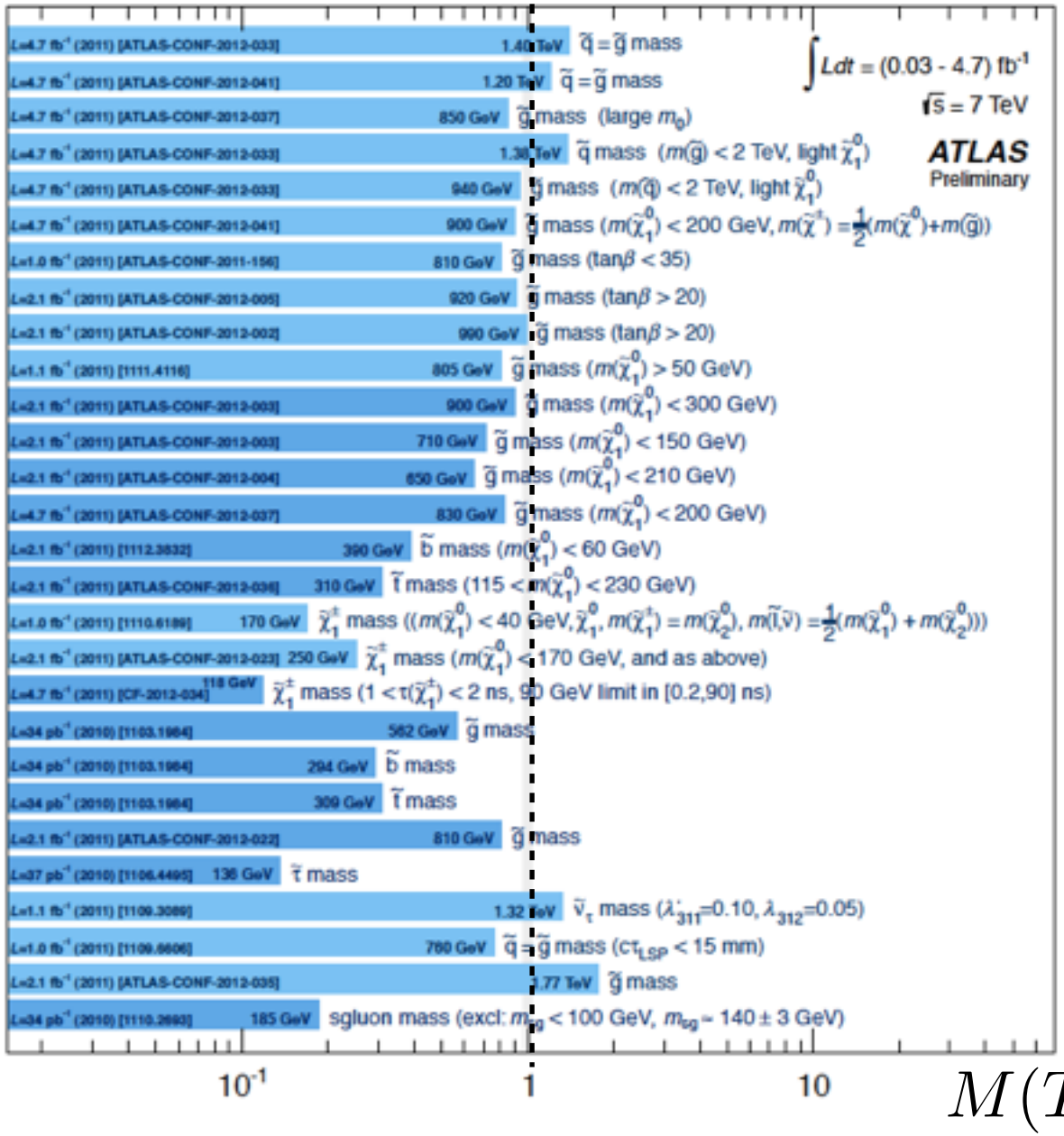
Azatov, Contino et al

Is it the SM up to very high energies?

ATLAS example for SUSY searches

$$\frac{7\ TeV}{6} \approx 1.2\ TeV$$

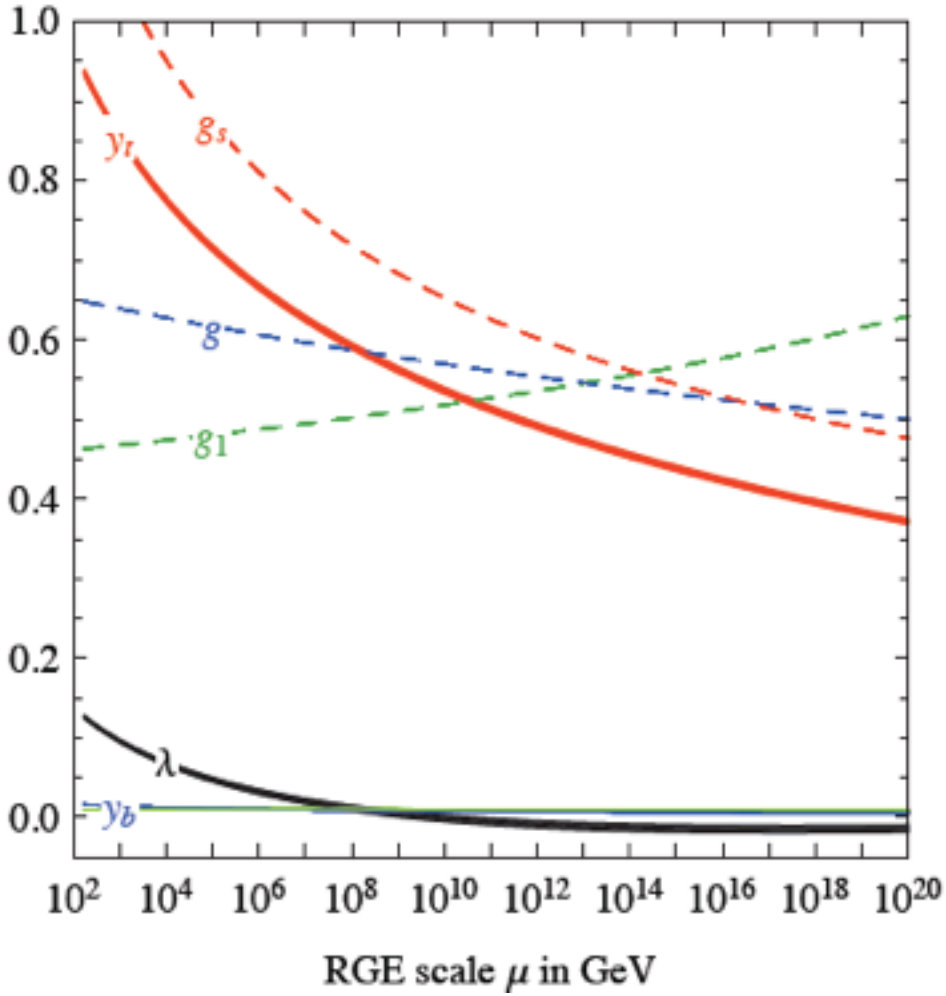
(See tomorrow)



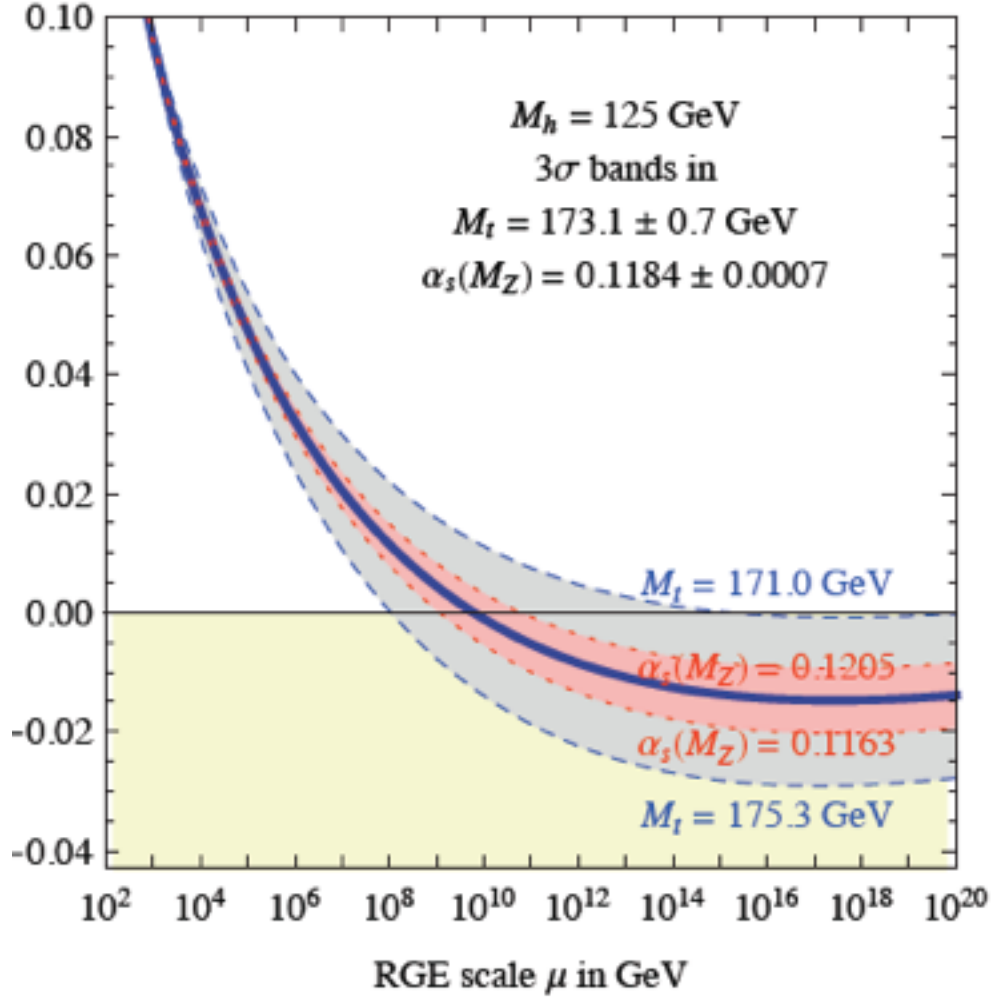
Very surprising if this were the case! Nevertheless...

The SM unchanged up to very high energies

largest couplings



Higgs self-coupling



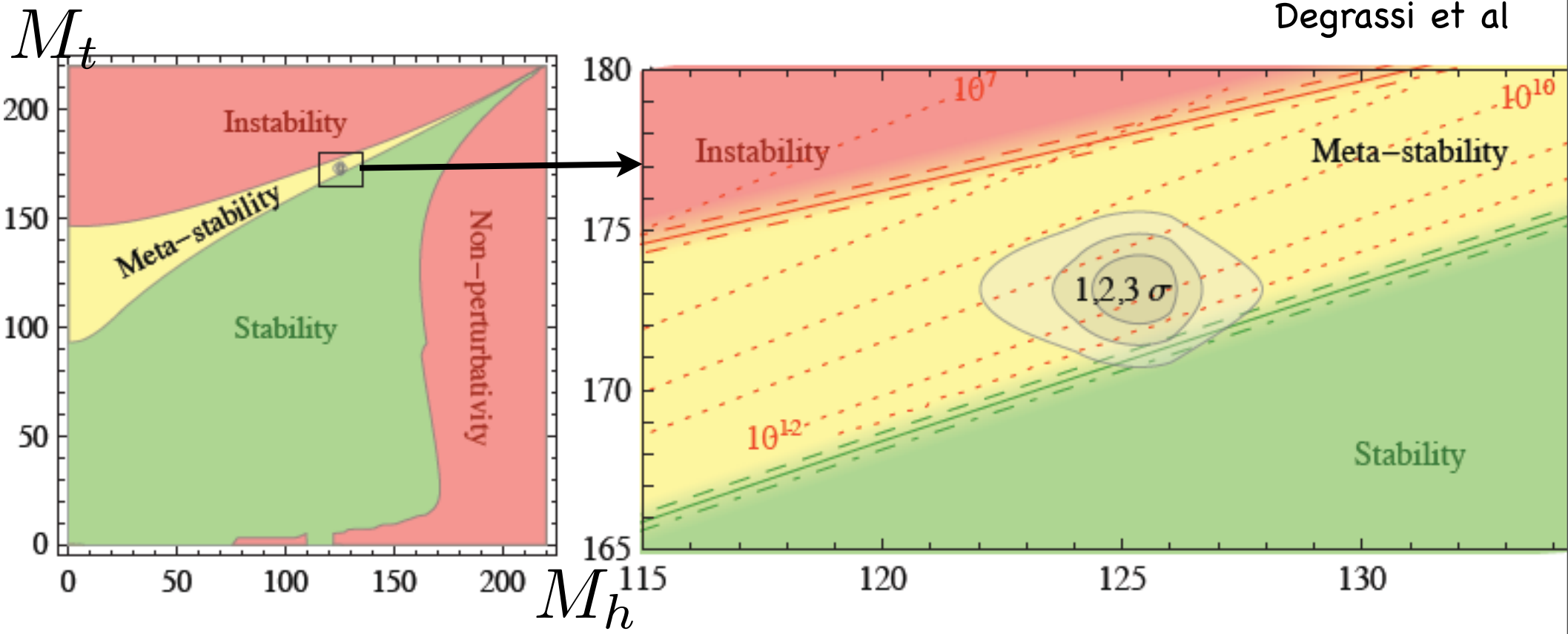
most accurate calculation to date

Degrassi et al

A special meaning for λ≈0 at MPl?

Assume SM unchanged up to M_{Pl}

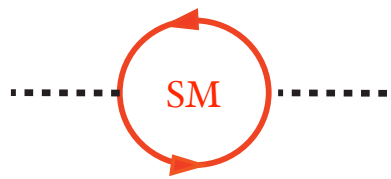
Degrassi et al

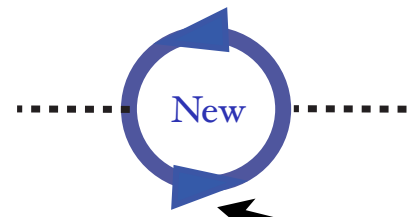


Absolute stability at $M_{Pl}(\lambda(M_{Pl}) \gtrsim 0)$ not quite achieved for current "best" values of M_t and M_h

Speculations about possible meaning of all this not lacking

The Fine Tuning problem of the Fermi scale

$\delta m_H^2 \quad =$ 

$+$ 

in isolation grows like Λ^2
where $\Lambda \equiv$ the "cutoff"
i.e. the highest scale at
which the theory is valid:
a signal of the sensitivity of m_H

knows about Λ_{NP}
i.e. any higher physical scale
to which the Higgs boson
is possibly coupled
$M_{Pl}, M_{GUT} \ldots$ you name it

$$\delta m_H^2 \approx \frac{\lambda^2}{16\pi^2}\Lambda_{NP}^2$$

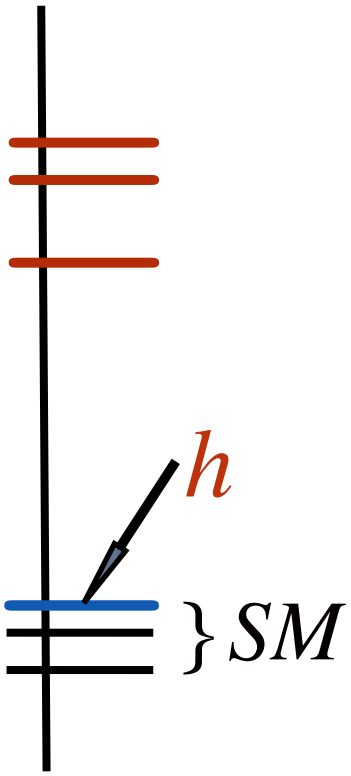
The ElectroWeak scale determined by the Higgs mass

Why $G_F^{-1/2} << \Lambda_{NP}$? Why $G_F^{-1/2} << G_N^{-1/2}$?

Another look at the FT problem

There are infinitely many theories at short distances, that give the same physics of the Standard Model, as long as their "low energy" spectrum coincides with the one of the SM

including the Higgs boson



We only know of approximate symmetries that can explain this

In all explicit examples, <u>without unwarranted cancellations</u>, new phenomena required at a scale Λ_{NP} not far from m_h

$\Rightarrow$ What are and where are they?

The (many) reactions to the FT problem

0. Ignore it and view the SM in isolation
   (if no other short distance scale, what about gravity?)

1. Cure it by symmetries: SUSY, Higgs boson as PGB

2. A new strong interaction nearby

3. A new strong interaction not so nearby: quasi-CFT

4. Saturate the UV nearby: extra-dimensions around the corner

5. Warp space-time: RS

6. Accept it: anthropic selection, the multiverse,
   the 10^{120} vacua of string theory

Anything else?