LHC theory vision talk

Higgs Hunting 2013
July 25/27, Orsay

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SNS and INFN, Pisa

The theory community after the first LHC phase

(Savas Dimopoulos, GGI, July 2013)

Is it the coronation of the SM or a step on a road still largely unexplored?

1. Completing the spectrum of the SM

$\Psi_i =$

$J = 1/2$

u	d	$e(1897)$	$\nu_e(1956)$
$c(1974)$	s	$\mu(1937)$	$\nu_\mu(1962)$
$t(1994)$	$b(1977)$	$\tau(1975)$	$\nu_\tau(2000)$

$J = 1$

$G^a_\mu(1978)$	$A_\mu(1905)$	$W_\mu(1984)$	$Z_\mu(1984)$

$J = 0$

$h(2012)$

Is it the coronation of the SM or a step on a road still largely unexplored?

2. The reasons for the discontent

$$\mathcal{L}_{ST} = |D_\mu h|^2 - m^2 h^2 - \lambda h^4 + \lambda_{ij}\Psi_i\Psi_j h \; (+\Lambda^4)$$

how natural?

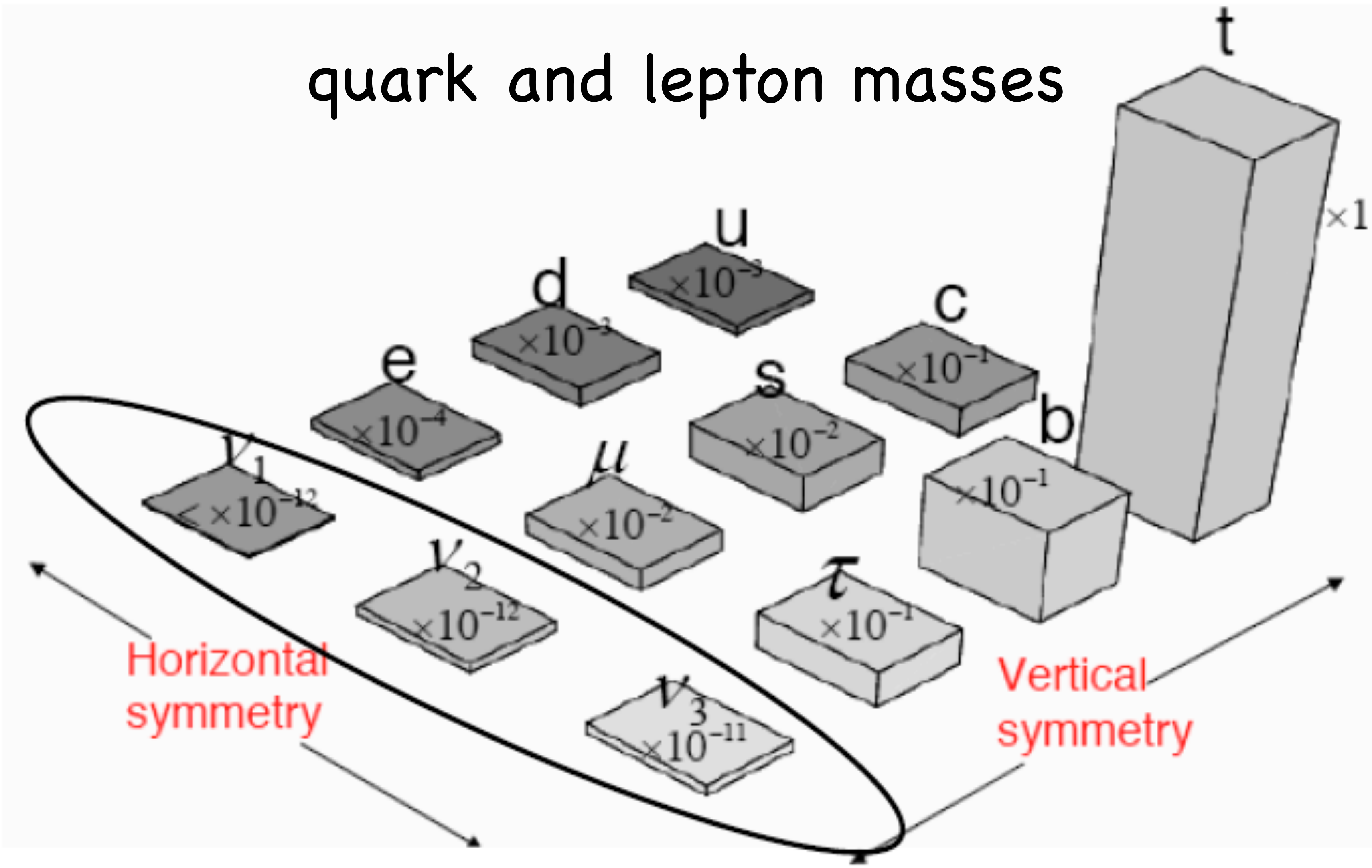
which dynamics, if any?

how about the flavour puzzle?

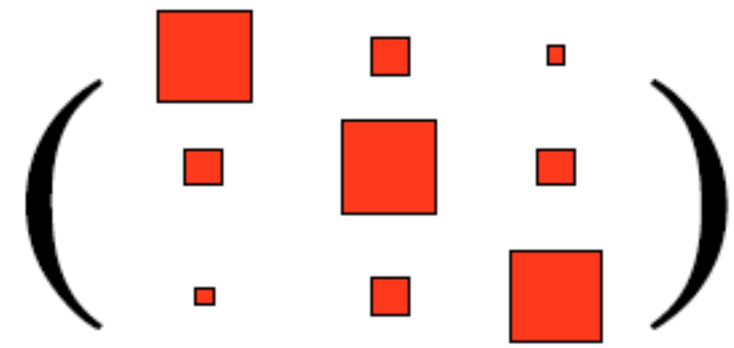
(Note: no physical inconsistency!)

A paradoxical answer: yes to both alternatives

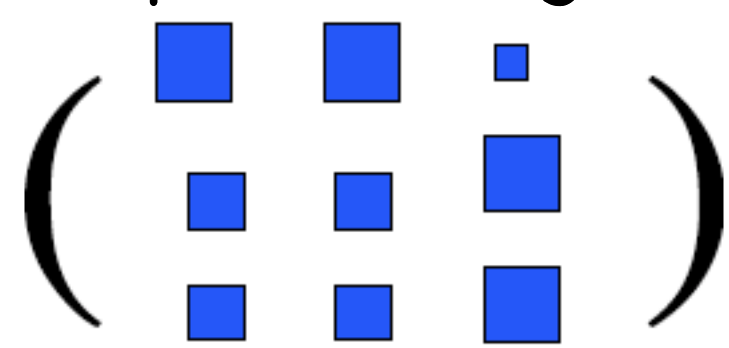
The flavour puzzle $\lambda_{ij}\Psi_i\Psi_j h$



quark mixings



lepton mixings



Every element in these pictures accounted for by an *ad hoc* parameter among the λ_{ij}

$m's, V_{CKM} \Leftrightarrow \lambda_{ij}^{Yukawa}$: a great embarrassment, unlikely to be solved without much needed key data

Flavour tests as very high-energy probes

$$\Delta\mathcal{L} = \Sigma_i \frac{1}{\Lambda_i^2}\mathcal{O}_i$$ (in absence of a flavour structure)

Lower bounds on Λ_i/TeV

	$\sin\phi = 0$	$\sin\phi = 1$
$\Delta S = 2$	$10^3 \div 10^4$	$2(10^4 \div 10^5)$
$\Delta C = 2$	$(1 \div 5)10^3$	$(0.3 \div 1)10^4$ $[(1 \div 5)10^4]$* ◇
$\Delta B_d = 2$	$(0.5 \div 2)10^3$	$(1 \div 3)10^3$
$\Delta B_s = 2$	$(1 \div 5)10^2$	$(3 \div 8)10^2$ $[(0.5 \div 2)10^3]$*
$\mu \to e\gamma$	$0.5 \cdot 10^3$ $[5 \cdot 10^3]$ **	

- bounds on $\Delta F = 1$ at $10 \div 100$ TeV
- range depends on Lorentz structure of $\mathcal{O} = \bar{f} f \bar{f} f$
- [ ]* = expected LHCb sensitivity(?)

◇ if $(|\frac{p}{q}|_D - 1) \lesssim 10^{-3}$ in the SM defendable (!?)

- [ ]**= expected from MEG upgrade(?)

Any deviations from CKM related to TeV physics?

Yes, if some flavour structure operative
(MFV and $U(2)^3$, alignment, ...)

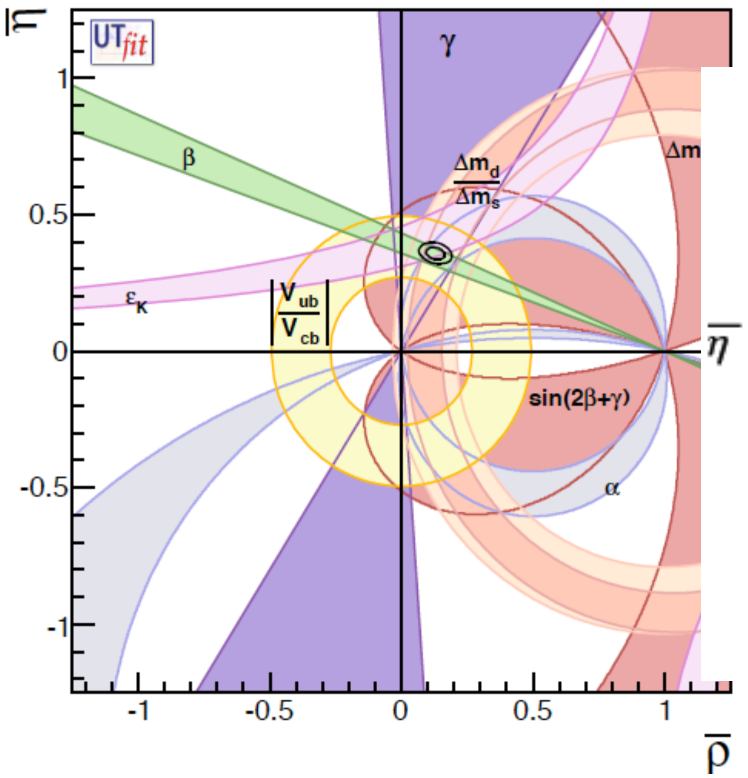
Relevant observables, competitive with current direct searches

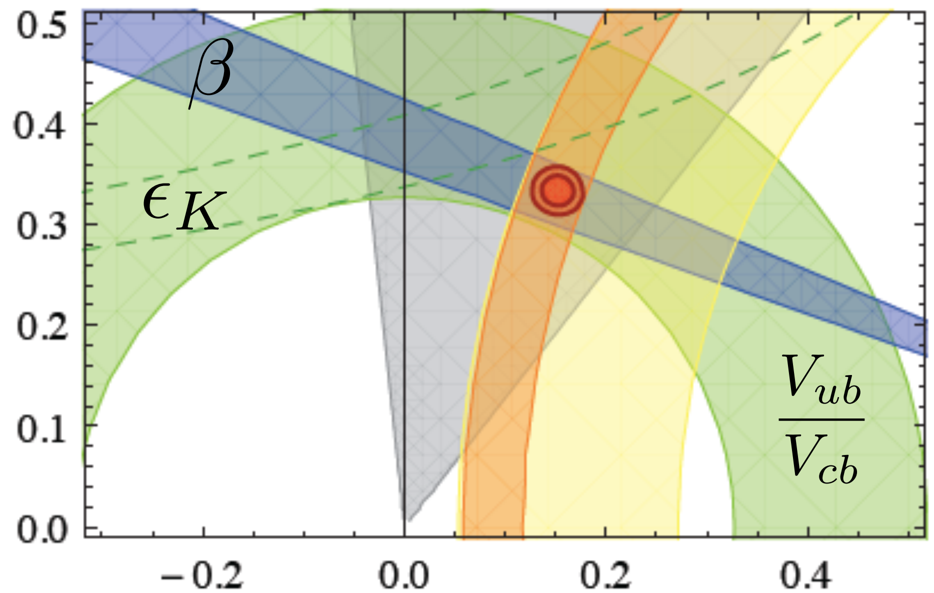
	ϵ_K $\Delta M_{d,s}$	$\phi_{d,s}$ $\Delta B = 2$	$\frac{\Delta M_d}{\Delta M_s}$ $\phi_d - \phi_s$	ΔM_c ✔ ϕ_c	$B \to X_s \gamma$ $B \to X_s \mu^+ \mu^-$ $B_s \to \mu^+ \mu^-$	$K \to \pi \nu \nu$	$\mathcal{A}_{CP}^{direct}(D)$ ✔
$U(2)^3$	Yes*	Yes	No	No	Yes*	Yes	No

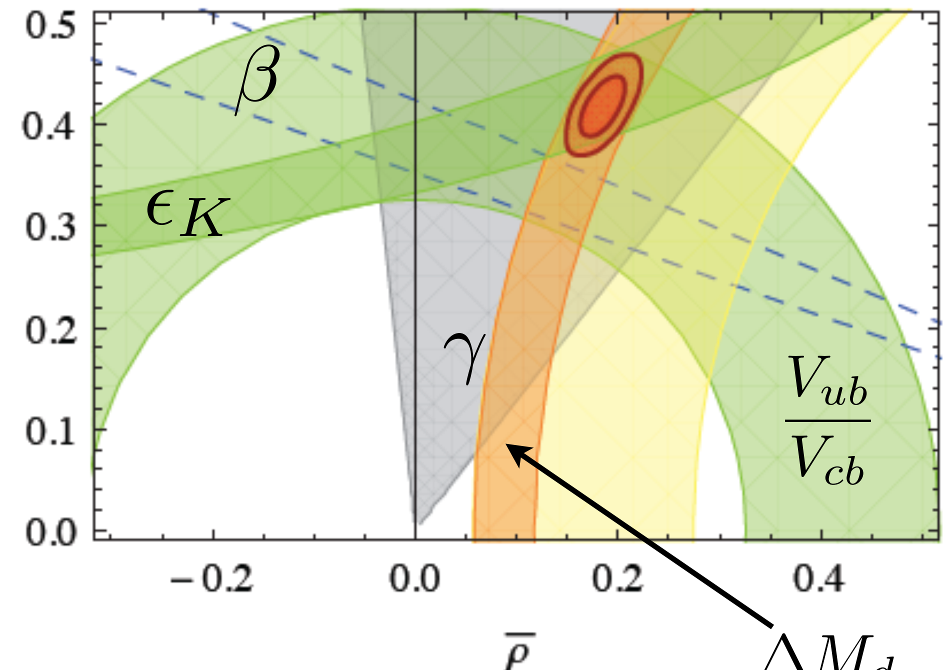
- * Some effects possible in $U(3)^3$ as well
- ✔ If SM under control

B, Buttazzo et al

$\Delta F = 2$ key measurements







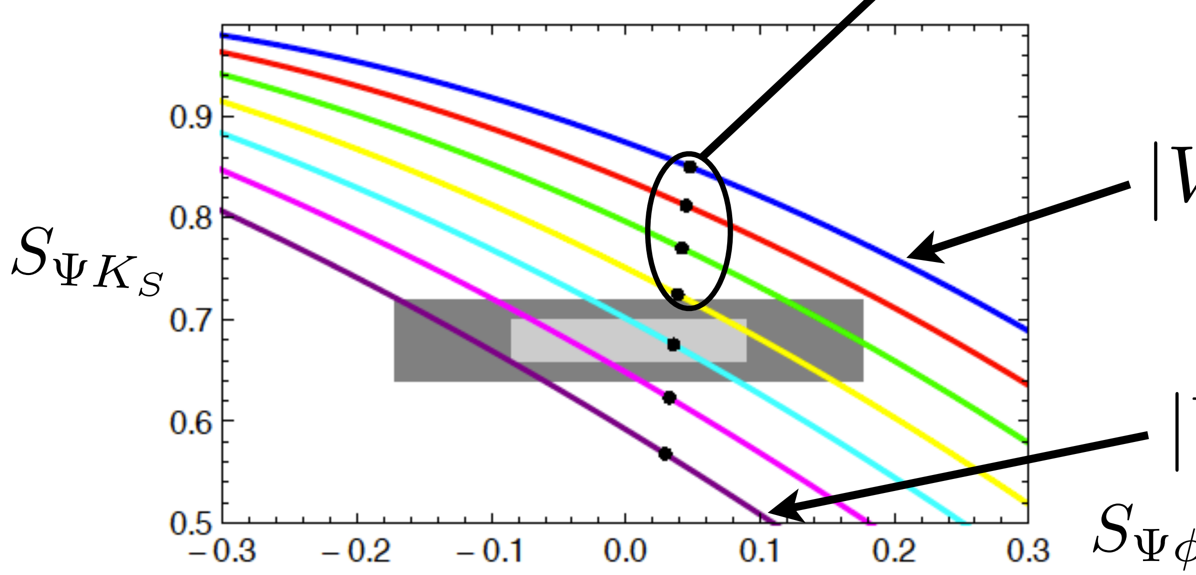
$\frac{\Delta M_d}{\Delta M_s}$

$\Rightarrow \gamma \approx 70^0$

$U(2)^3$

SM centered on ϵ_K

The key role of V_{ub} and $S_{\Psi\phi}$ as well as of $F_{B_{d,s}}(B_{d,s})^{1/2}$ from the lattice



$|V_{ub}| = 0.0046$

$|V_{ub}| = 0.0028$

Buras, Girrbach

The (many) reactions to the Fine Tuning problem

CERN June 2011

(untenable)

0. Ignore it and view the SM in isolation

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

(new)

2. ~~A new strong interaction nearby (TC)~~

3. ~~A new strong interaction not so nearby: quasi-CFT (ETC)~~

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

5. Warp space-time: RS

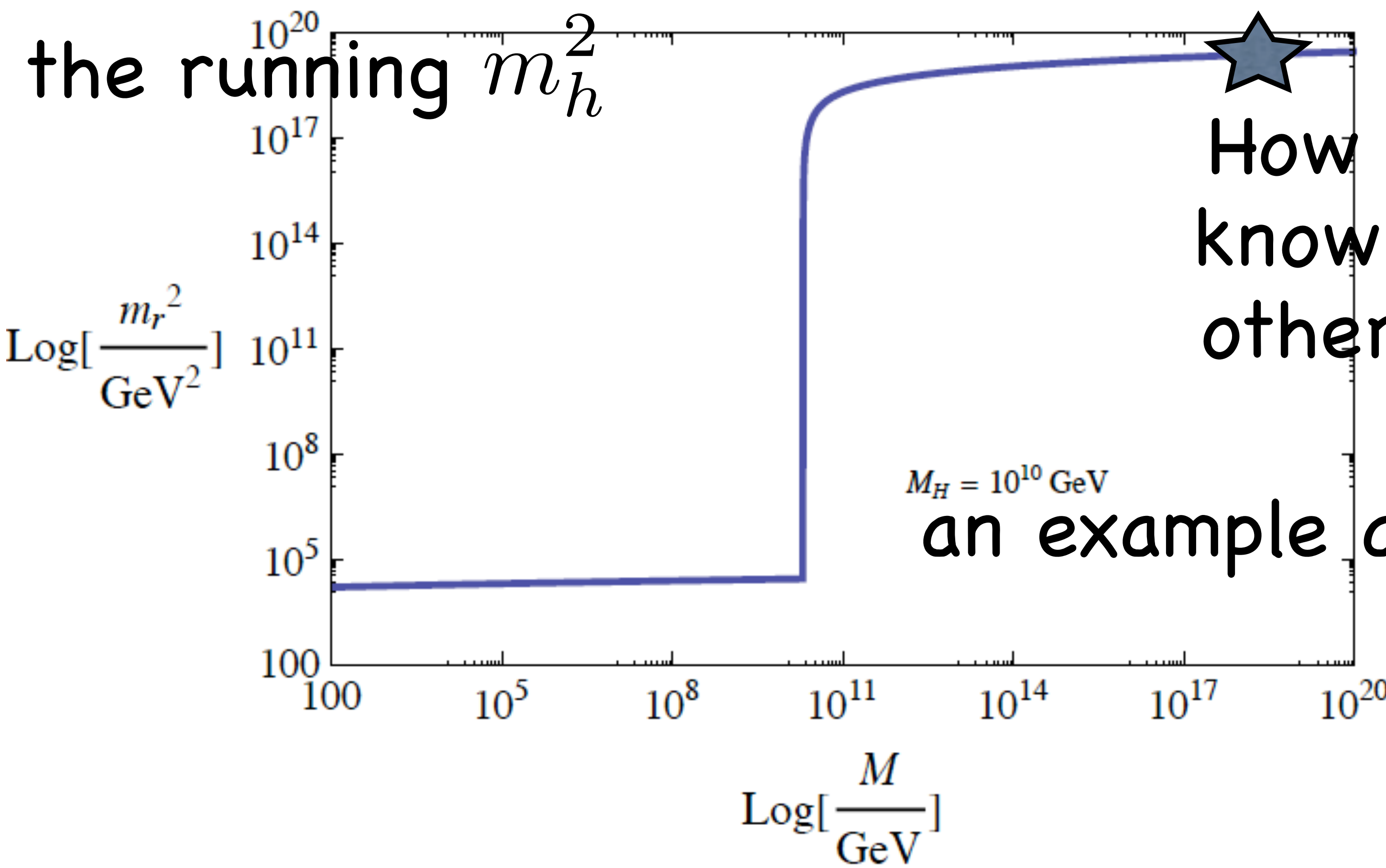
6. Accept it: the multiverse, the 10^{120} vacua of string theory

Anything else?

The Fine Tuning, once again

Never a problem of quadratic divergences !, but a threshold effect due to any short distance physics that couples to the Higgs boson

the running m_h^2



How can an initial condition here know precisely about M_H or any other new threshold above m_h ?

an example at $M_H = 10^{10}\ GeV$

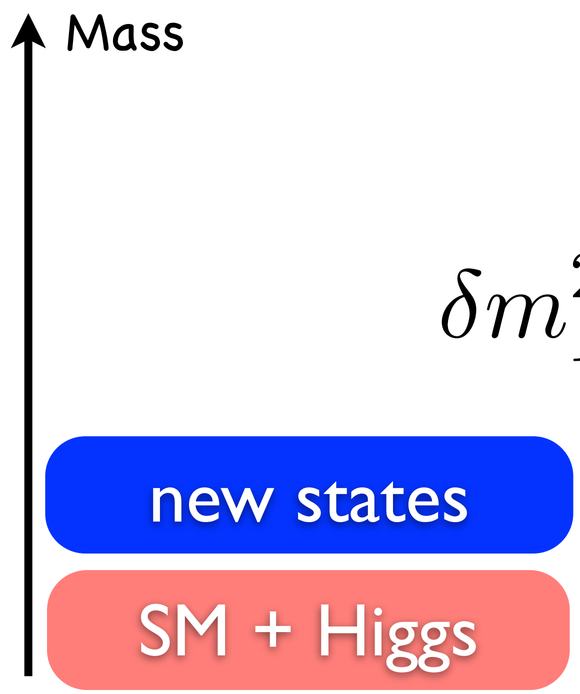
B, 1996

1. One does not have to care if the Higgs mass is protected
2. Perhaps there is NO such threshold and gravity is gentle enough
3. Only M_H close enough to m_h or sufficiently decoupled (gravity?)

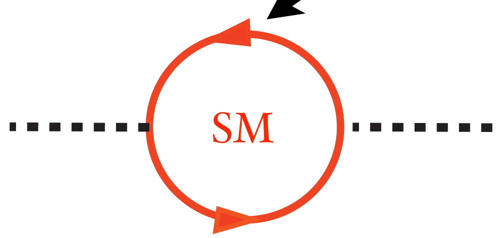
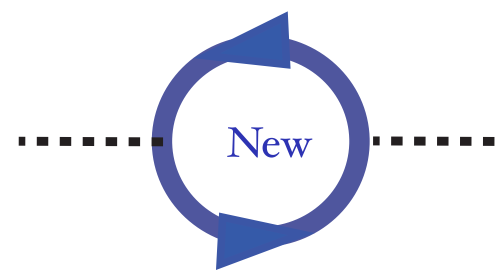
Shaposnikov et al

Farina, Pappadopulo, Strumia

A "natural", not Fine Tuned Higgs boson



mostly the top

$\delta m_H^2 =$  $+$  ~ 0

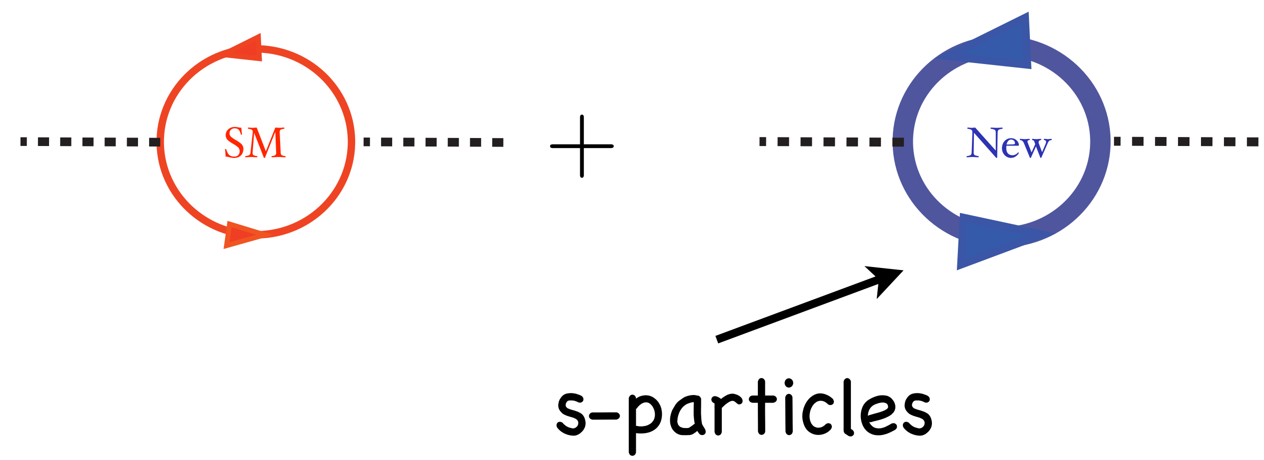
by an (approximate) symmetry

relative to any higher physical scale to which the Higgs boson is possibly coupled

If so, explain why the great empirical success of the SM does not depend on unknown short distance physics

Supersymmetry

$$\delta m_H^2 \quad = $$

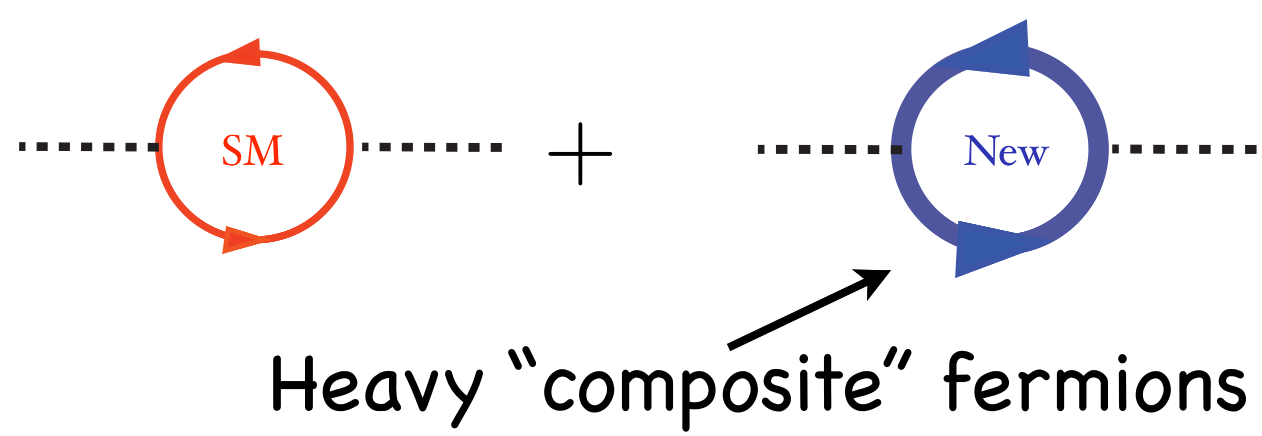


$$\sim \; 0$$

The Higgs boson as a pseudoGolsdtone

(like the π in QCD)

$$\delta m_H^2 \quad = $$



$$\sim \; 0$$

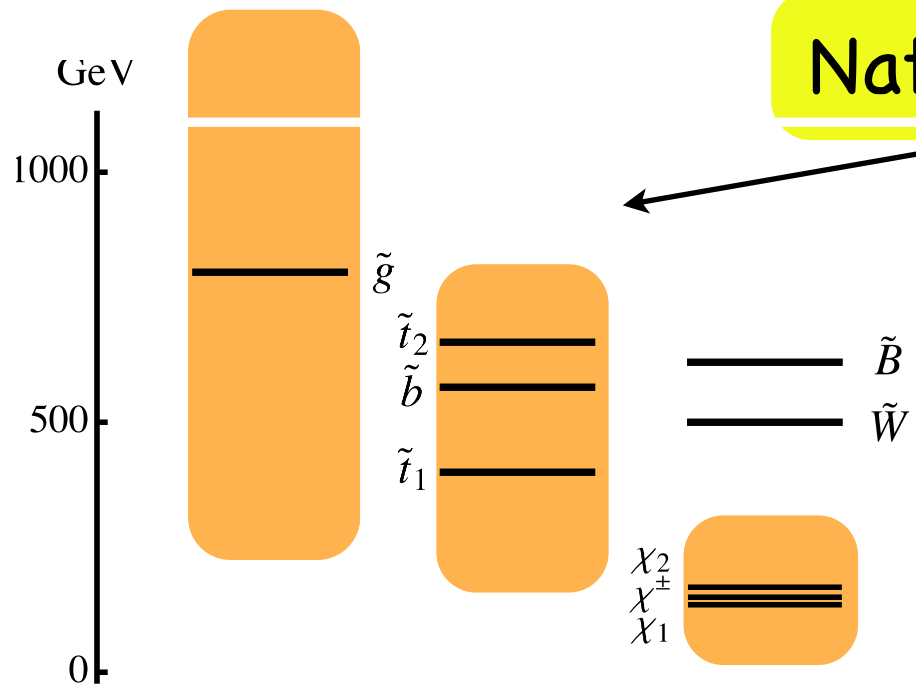
Question: Nothing seen so far. Shouldn't we worry?

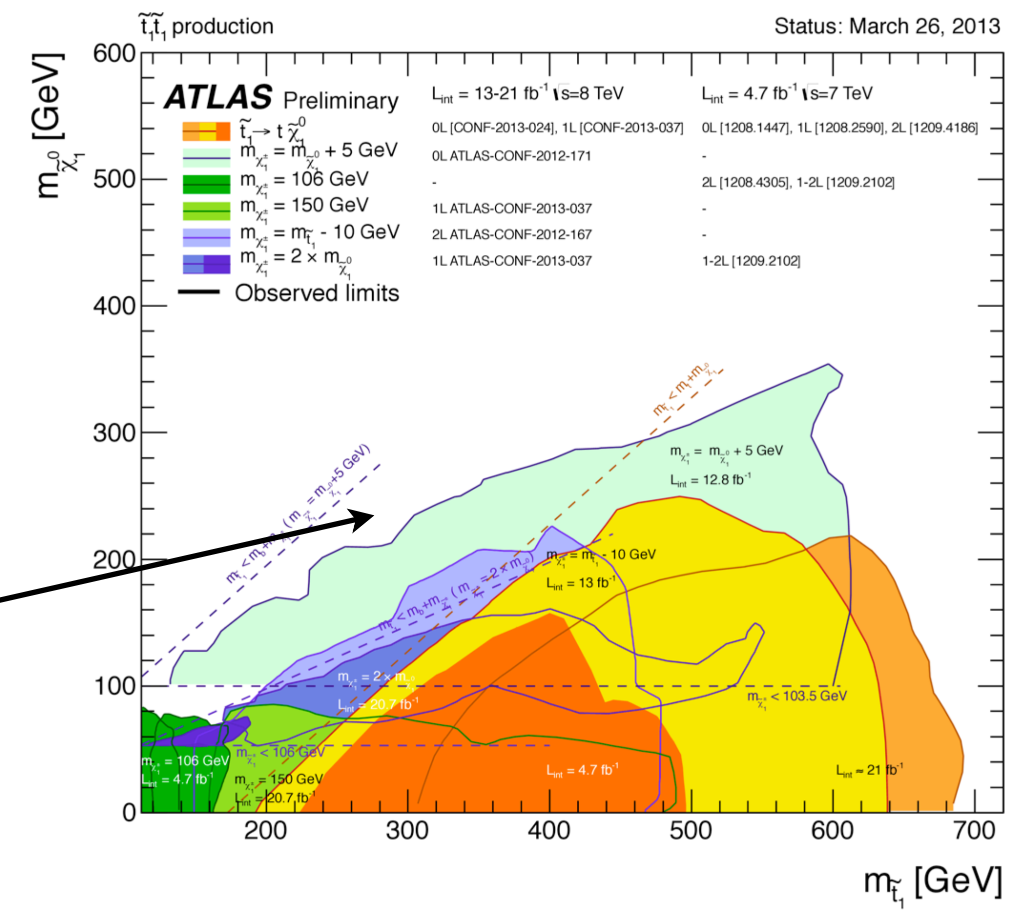
$$M_{New} \gtrsim 500 \div 1000 \; GeV$$

Answer: No theorem but this page still offers the driving criterium

Supersymmetry searches

Natural spectra

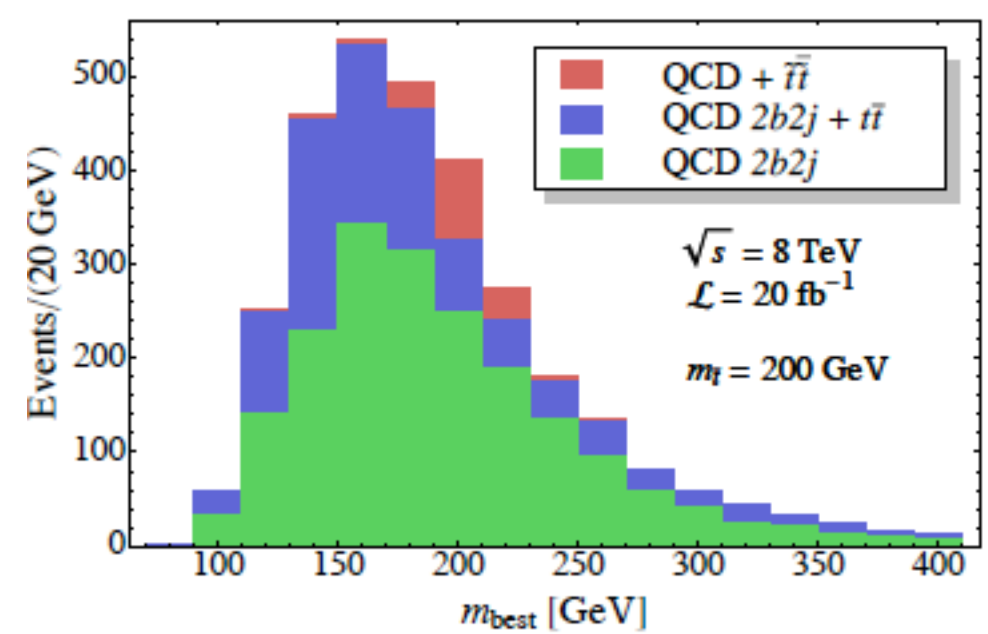




Compressed spectra

RPV in baryons only (with MFV)

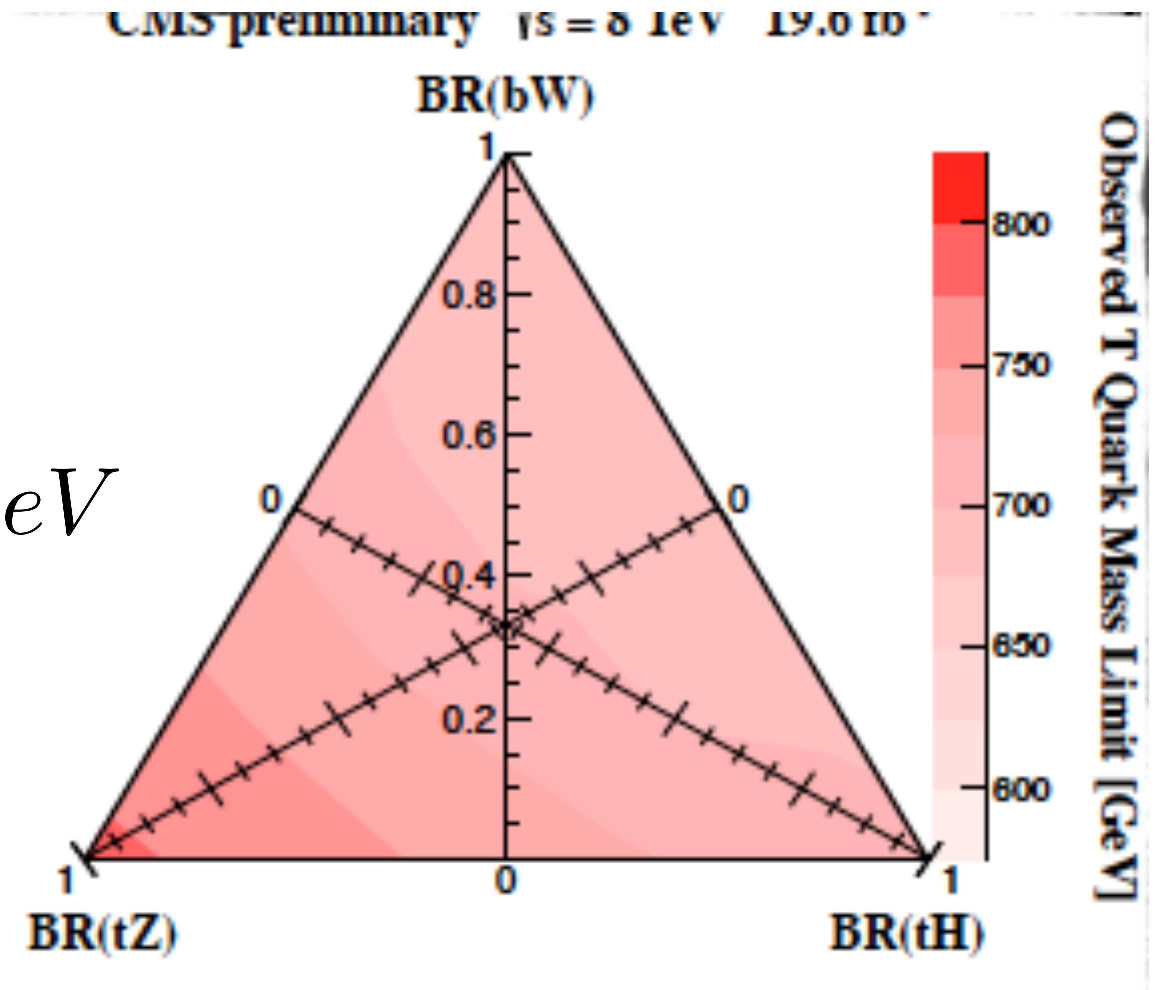
$$\tilde{t} \to b + s$$



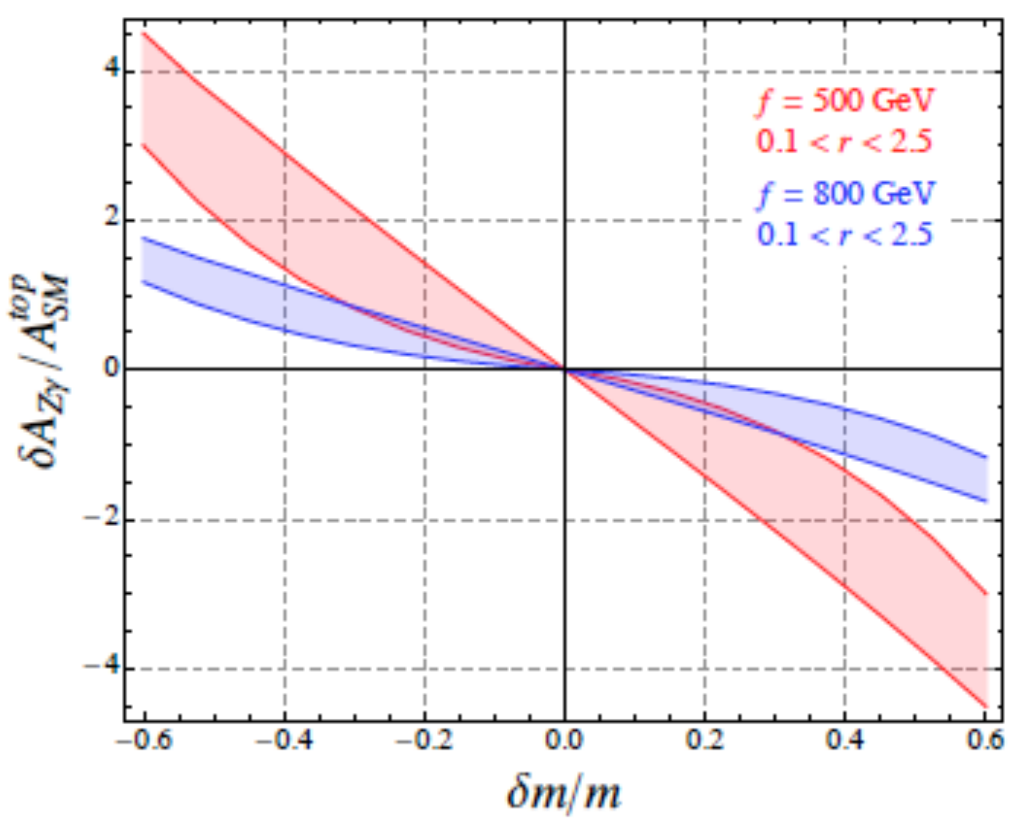
Csaki et al

Franceschini, Torre

Higgs-as-PGB searches



Top fermionic partners
currently $m_T > 600 \div 800\ GeV$



Indirect searches
$$h \to Z\gamma$$

Contino et al

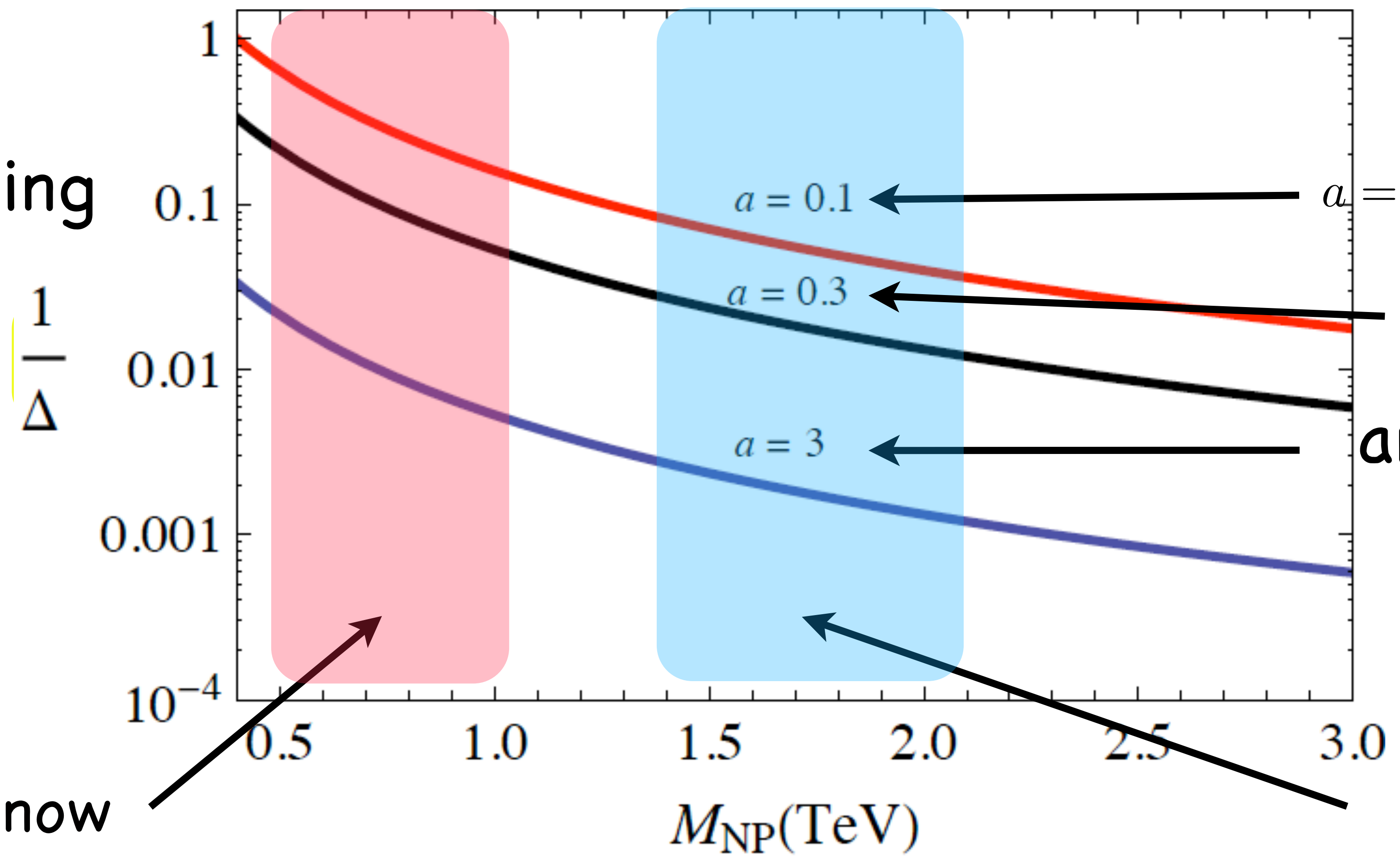
A quantitative measure (!?) of naturalness

$$\delta m_h^2 \approx a M_{NP}^2 < \Delta m_h^2$$

model dependent

a measure of fine tuning
(which exist in nature)

fine tuning



$a = \frac{3\lambda_t^2}{4\pi^2}$ hard to achieve

some NMSSM

an indicative MSSM

≈ LHC now

≈ LHC14 (?)

After which, in case, everybody will have to decide

(Split SUSY: a fine tuned MSSM, without discontinuity)

Can some extra Higgs bosons be the lightest new particles around?

The pro's for just one Higgs boson

1. simplicity

How about the 12 (18) matter and the 12 (3) vector states?

2. electromagnetism always preserved

From 2 to 3 phases only

3. flavour

No big reason to be proud of the λ_{ij}

4. a single tuning, in case

None is better, which often demands more Higgs bosons

Two ways to attack the problem

⇒ By direct search $pp \to h_{\neq LHC} + X$

$\hookrightarrow$ decay products

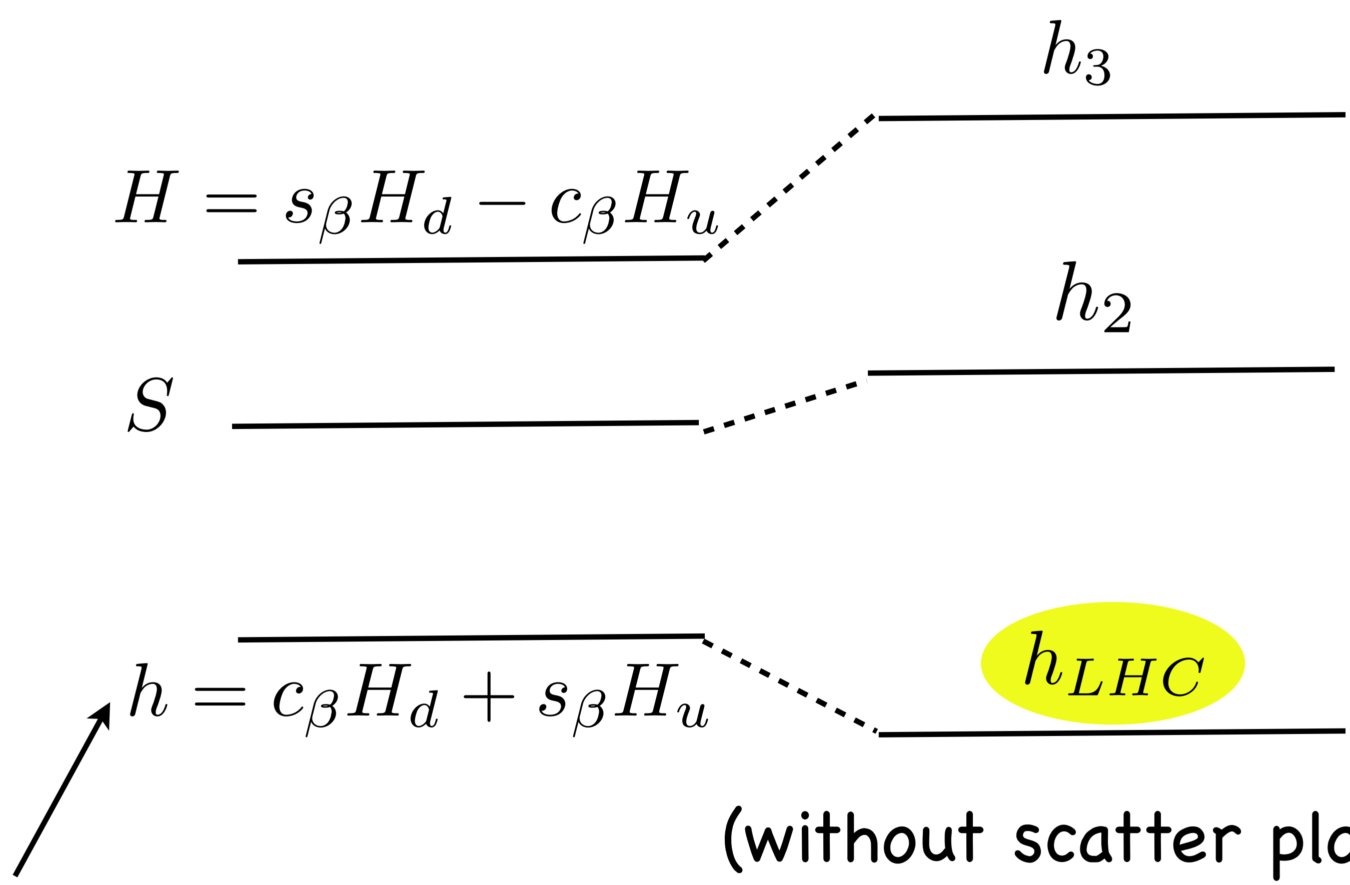
(perhaps itself in the decay products of...)

⇒ By precision measurements of the couplings of the 125 GeV (quasi-standard) Higgs boson

(the NMSSM example)

$\lambda S H_u H_d$

Fayet 1975



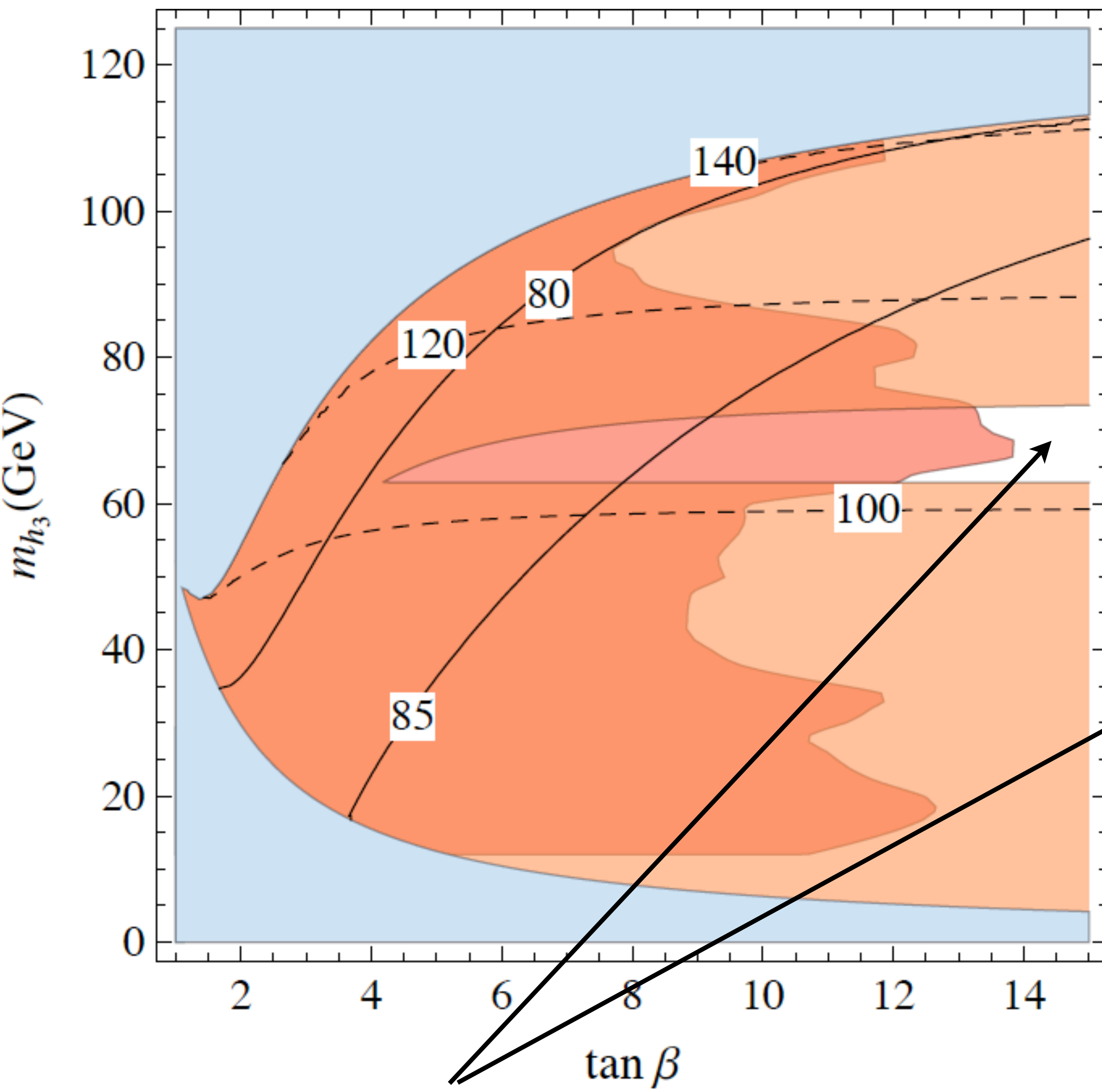
has SM properties

(without scatter plots or benchmark points)

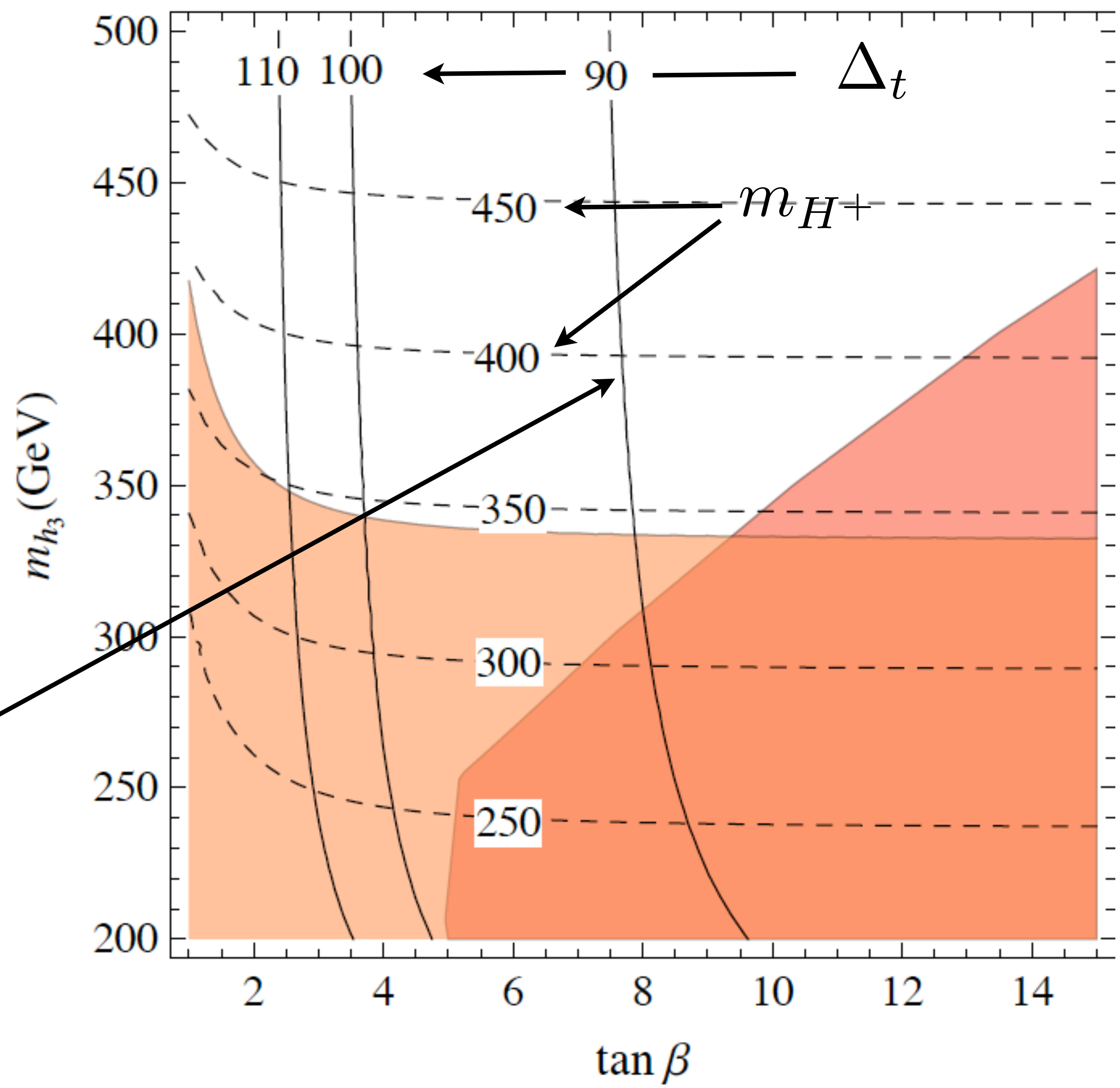
(Tesi talk)

MSSM at variable Δ_t and $\frac{\mu A_t}{< m_{\tilde{t}}^2 >} < 1$

$h_3 < h_{LHC}$



$h_{LHC} < h_3$

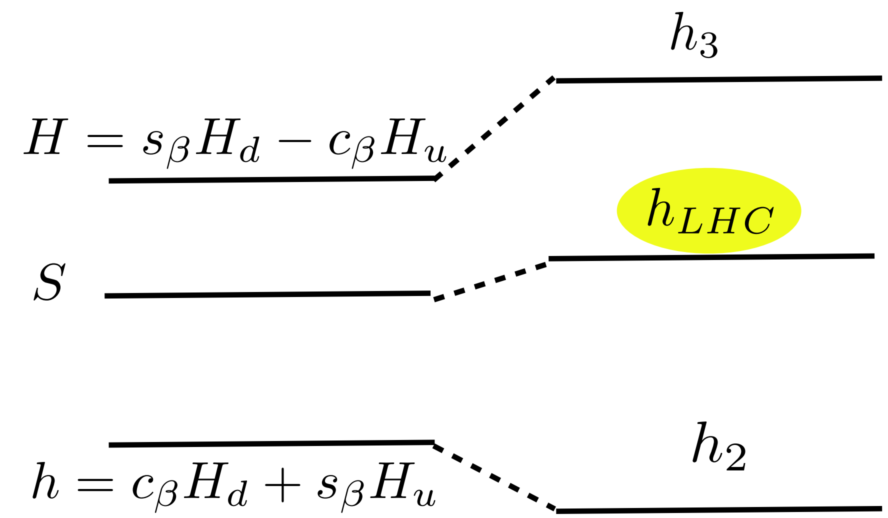


region still allowed
only for largish Δ_t

orange = excluded by h_{LHC} - measurements

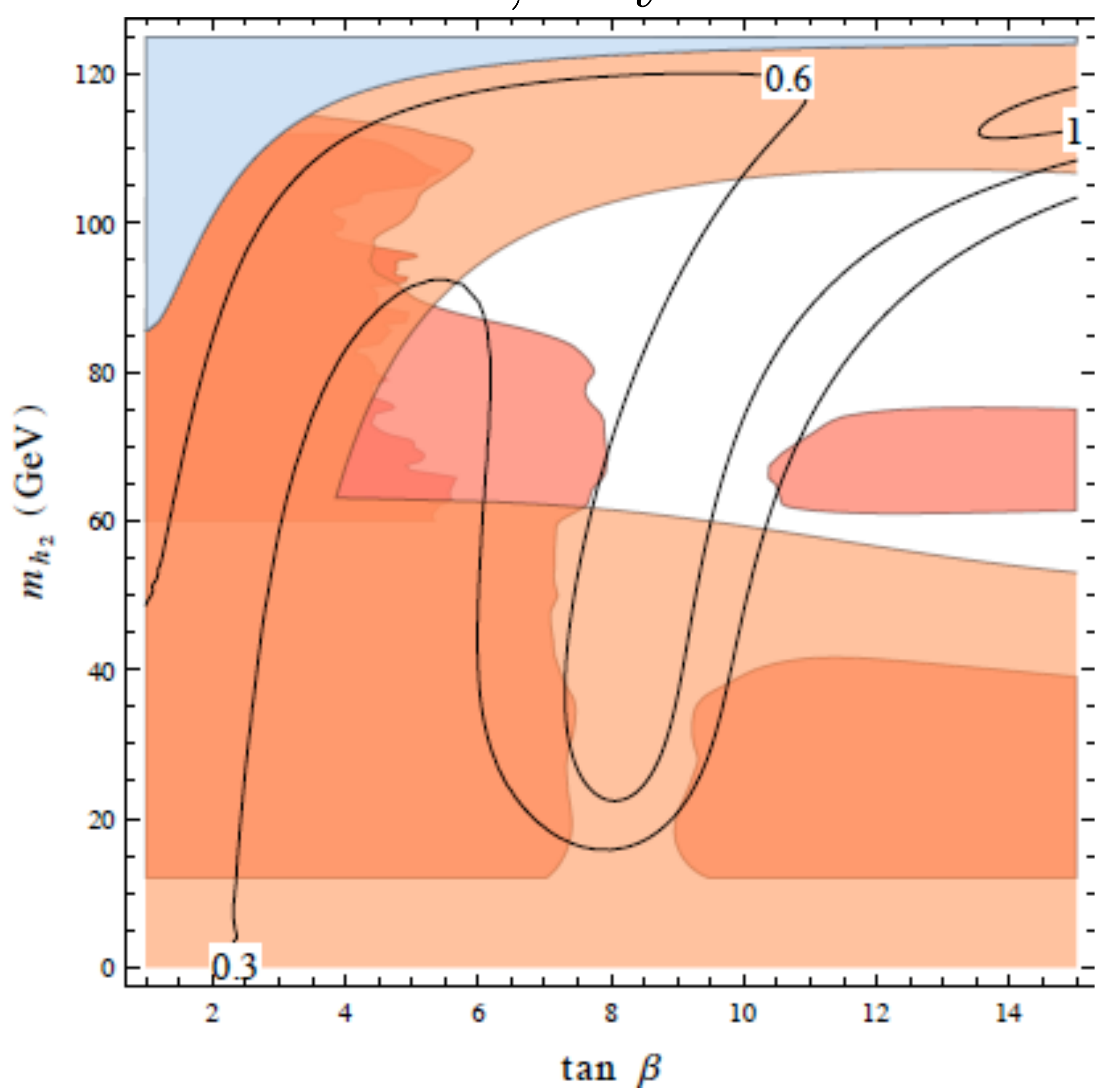
red = excluded by direct searches
LEP ($h_3 < h_{LHC}$) LHC ($h_{LHC} < h_3$)

Fully mixed case and the $\gamma\gamma$ signal

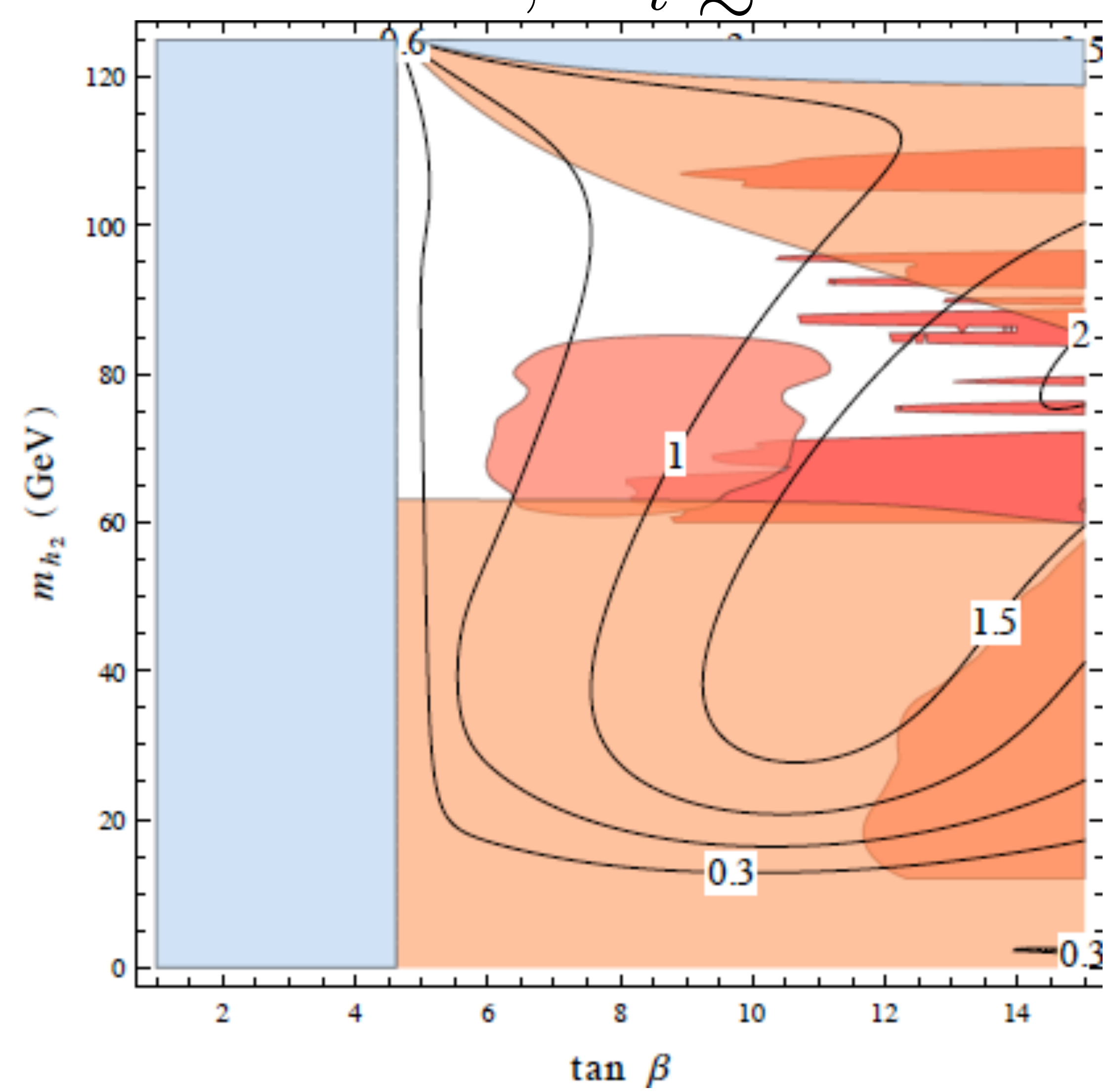


isolines of $\mu(h_2 \to \gamma\gamma)$ normalized to SM

$\lambda = 0.1,\ \Delta_t = 85\ GeV$



$\lambda = 0.8,\ \Delta_t \lesssim 75\ GeV$



orange = excluded by h_{LHC} - measurements

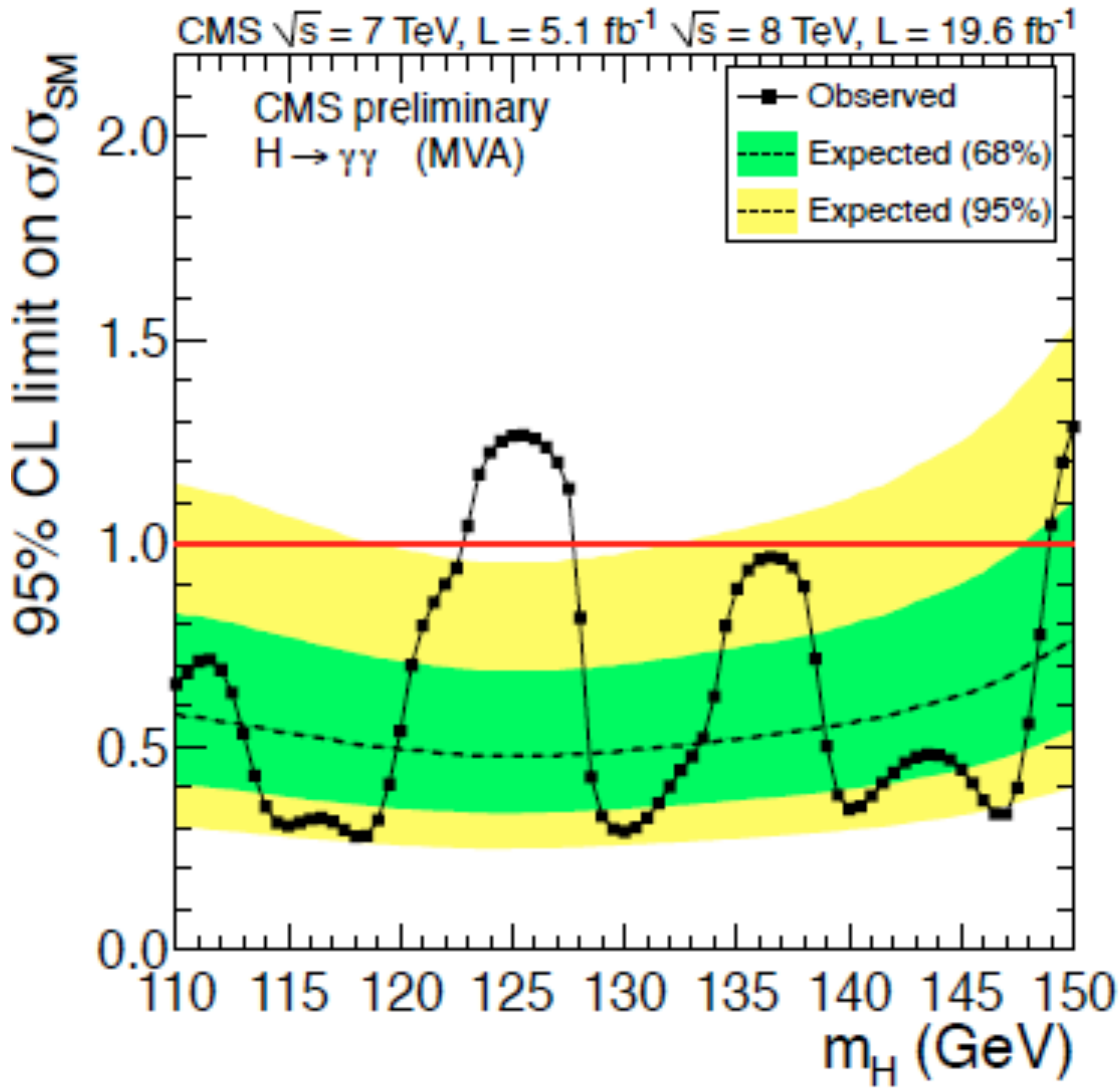
blue = unphysical

red = excluded by LEP in $h_2 \to b\bar{b}$

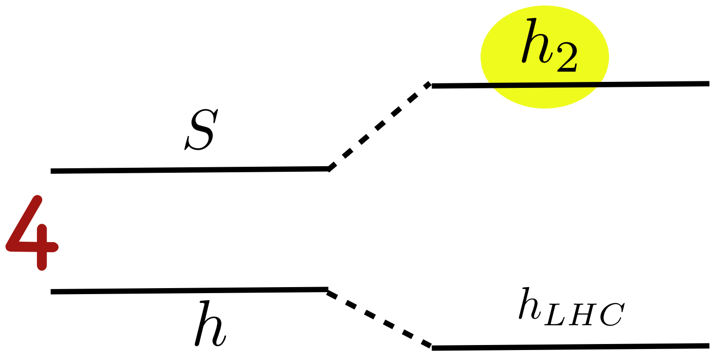
magenta = excluded by LEP in h_2 → hadrons

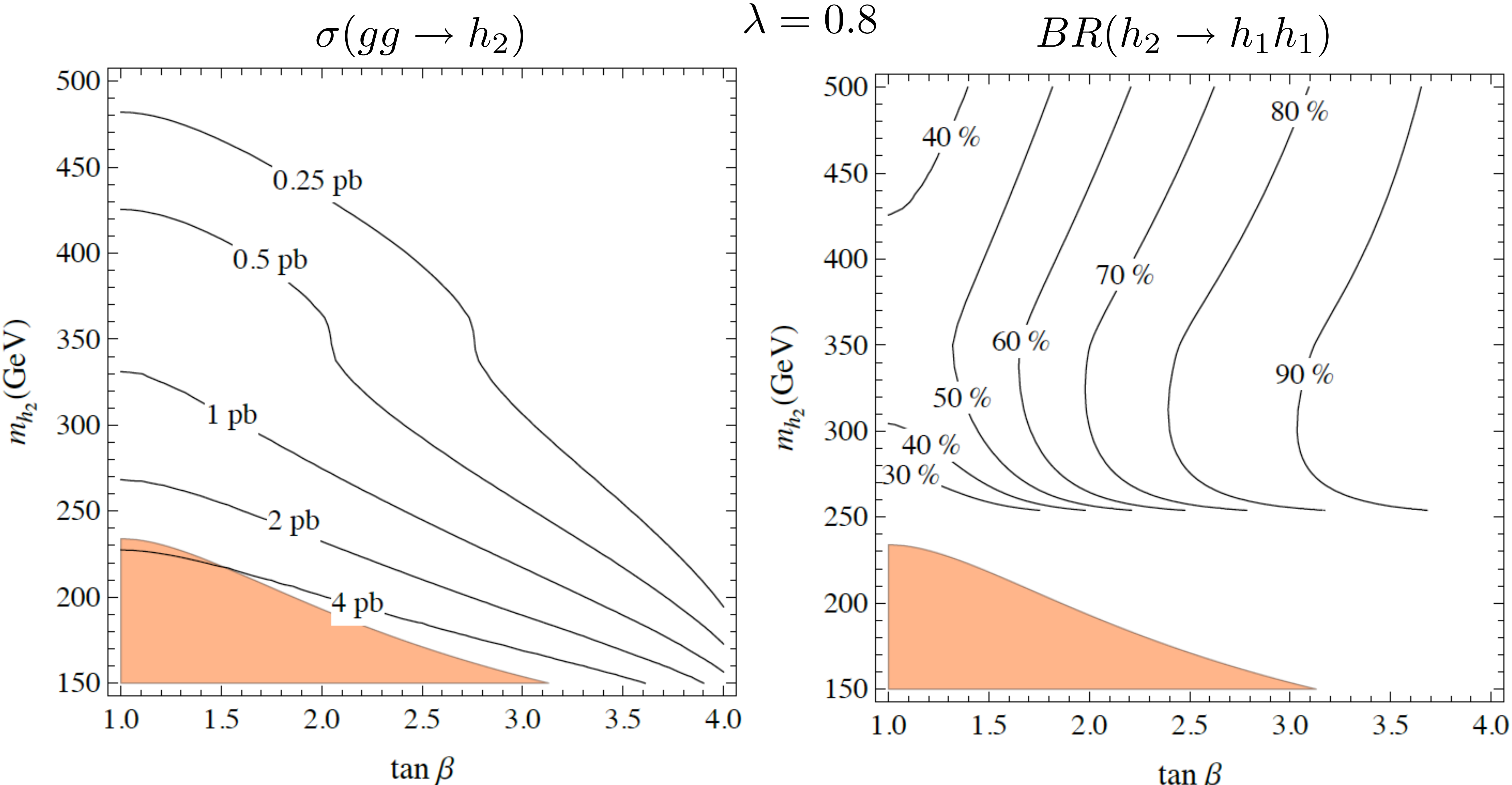
Insisting on $h_2 \to \gamma\gamma$ at lower energies might be useful

(Pokorski et al)



NMSSM: Direct search at LHC14



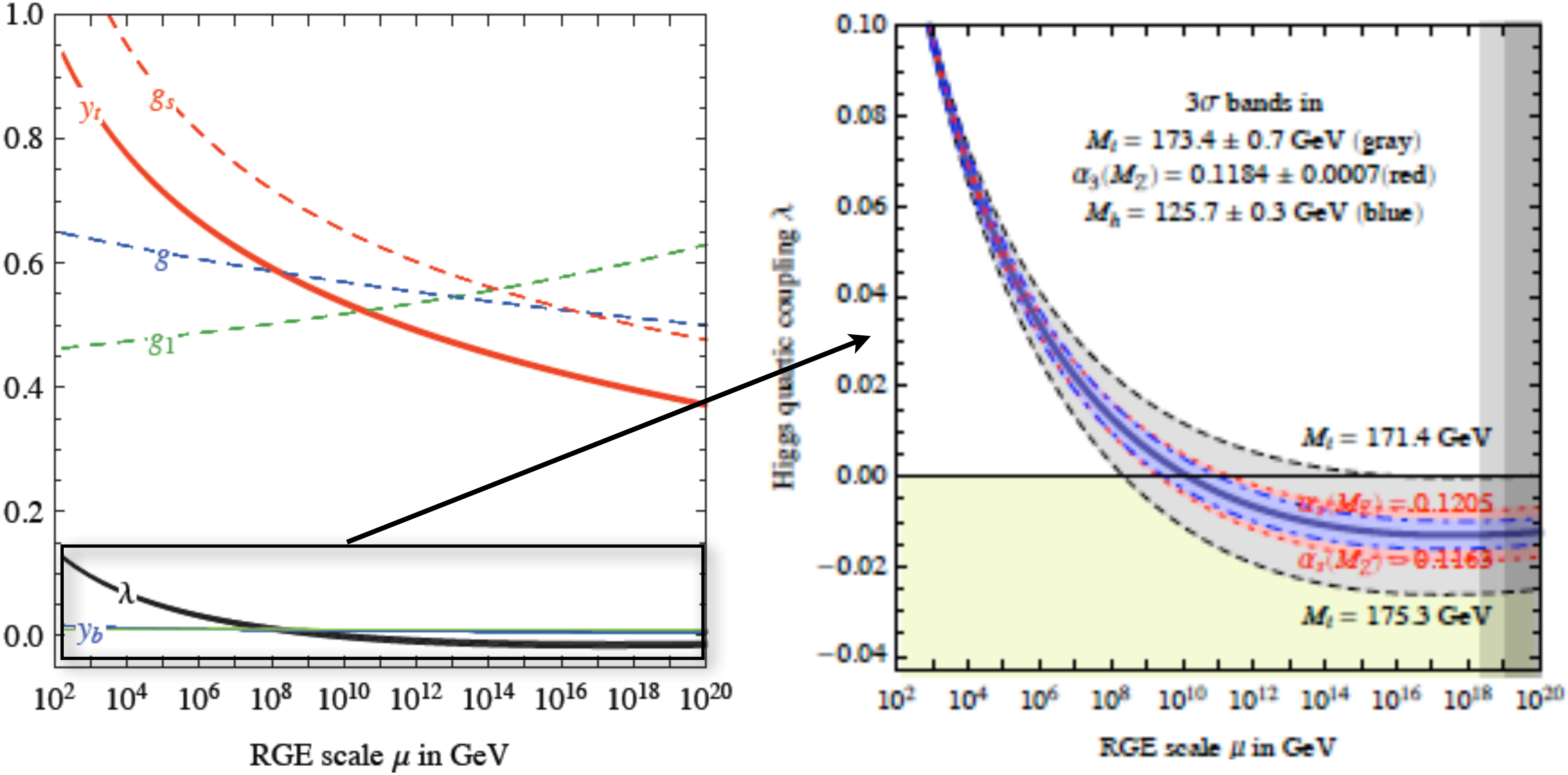


orange = excluded by h_{LHC} - measurements

any other BR determined in this plane

What if one does not care about naturalness and the SM is unchanged up to very high energies?

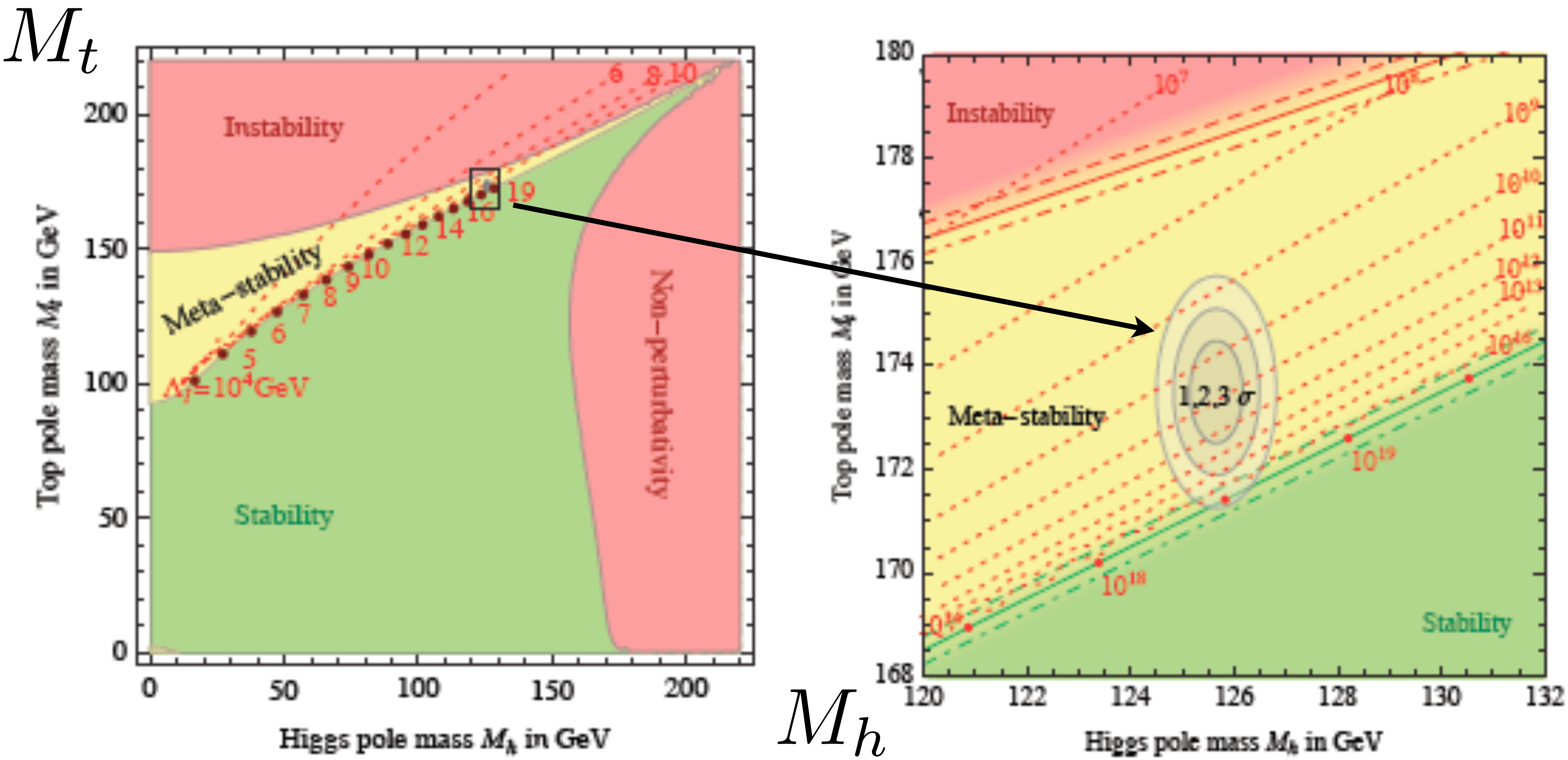
largest couplings | Higgs self-coupling



Degrassi et al 2012
Buttazzo et al 2013

Assume the ST unchanged up to M_{Pl}

The phase diagram of the Standard Model

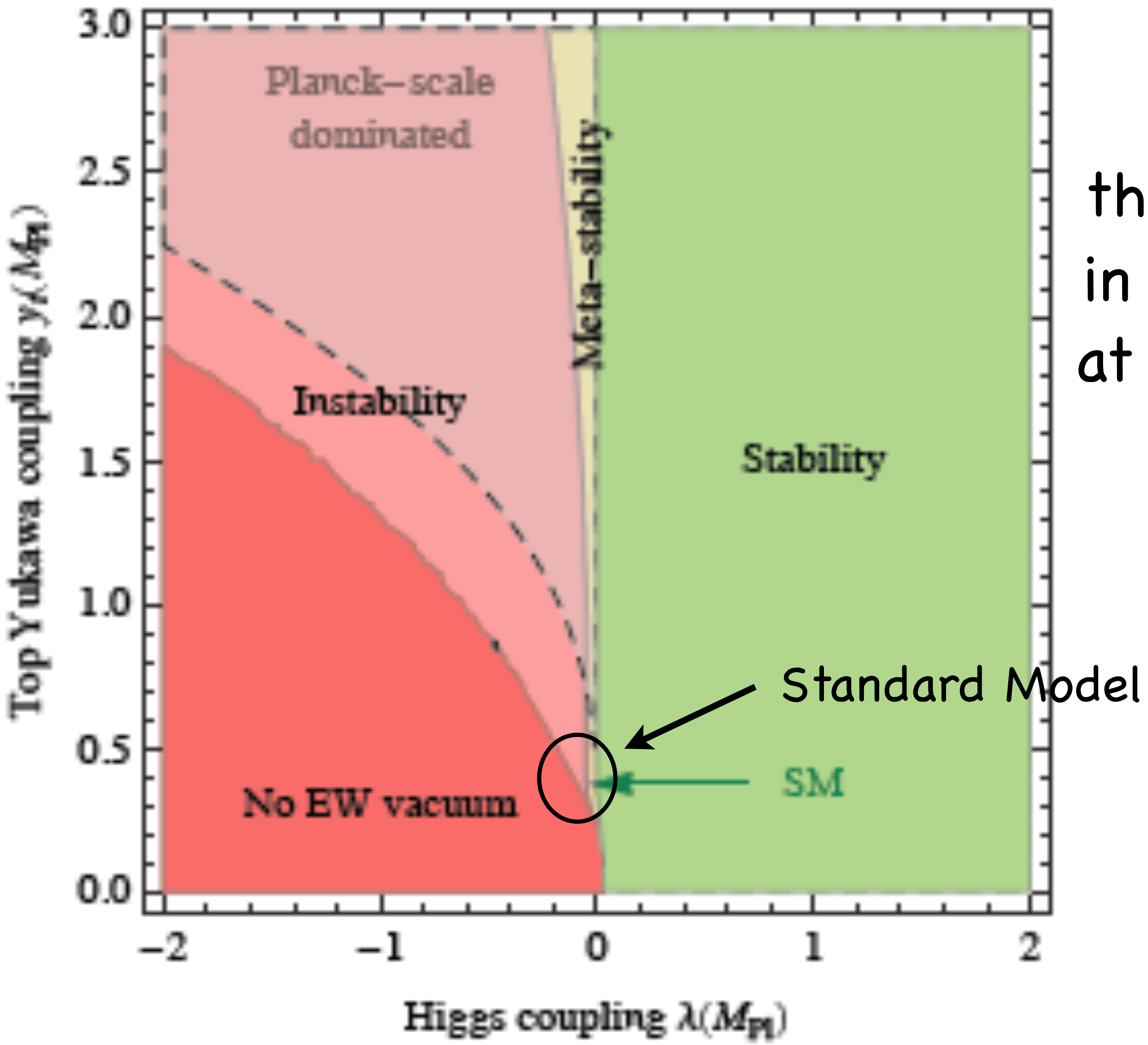


Buttazzo et al

Given the current values of M_t and M_h
the Universe seems to live in a peculiar meta-stable situation

If Big hypotheses accepted, what can one make out of this?

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia



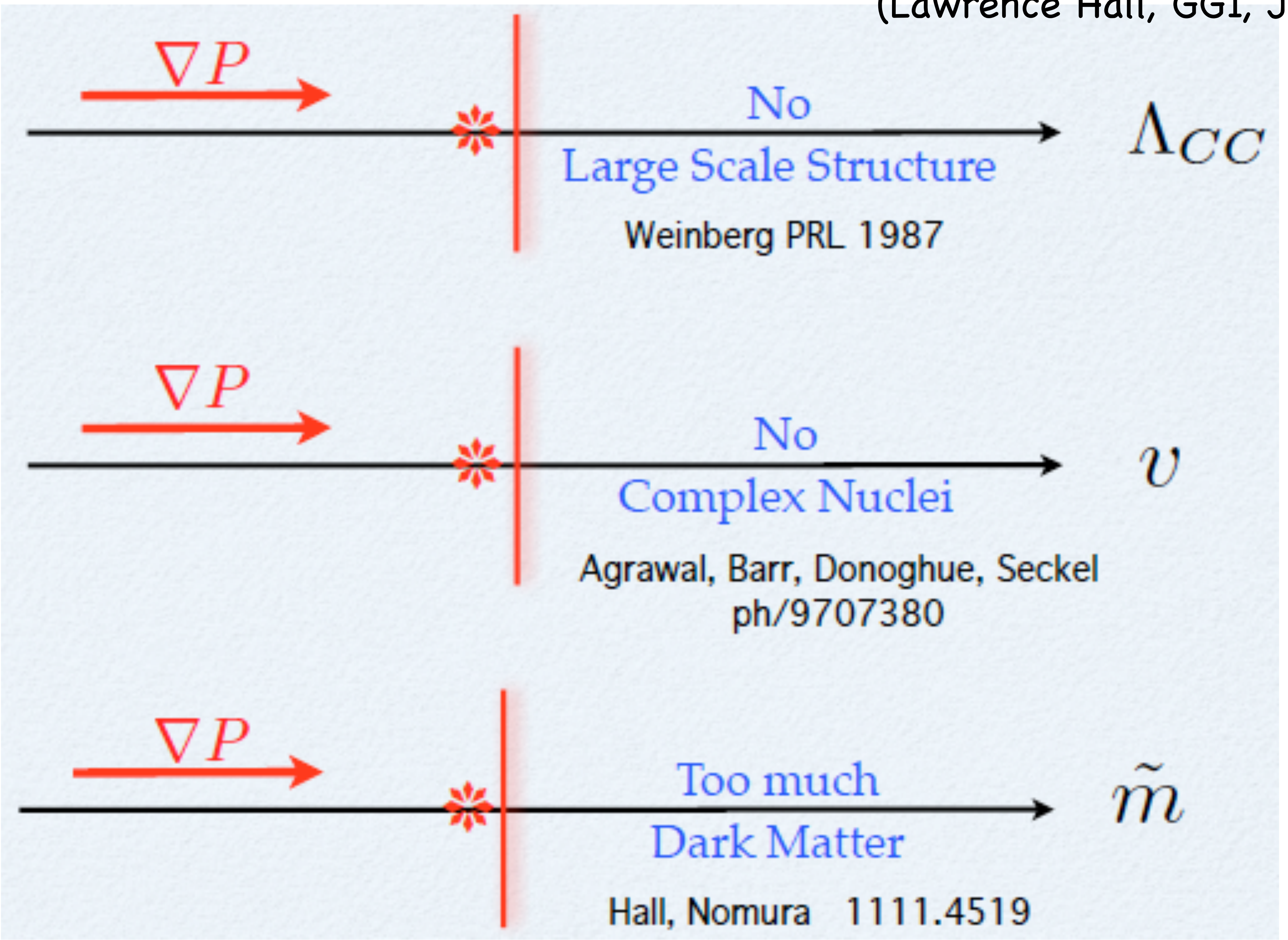
the same phase diagram as before in terms of Higgs and top couplings at the Planck scale

⇒ Our Universe (one in the "Multiverse") "near criticality"

(among other possibilities)

Anthropic pressure (as opposed to criticality)

(Lawrence Hall, GGI, July 2013)



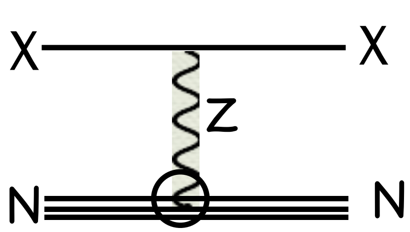
! Either way, a major shift in the way of doing physics !

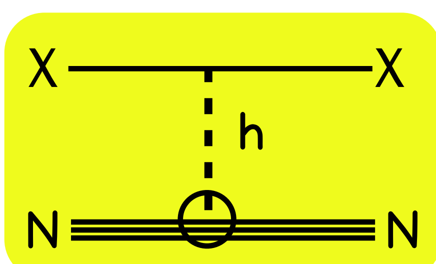
DM searches and the Higgs boson

$$\chi N \to \chi N$$

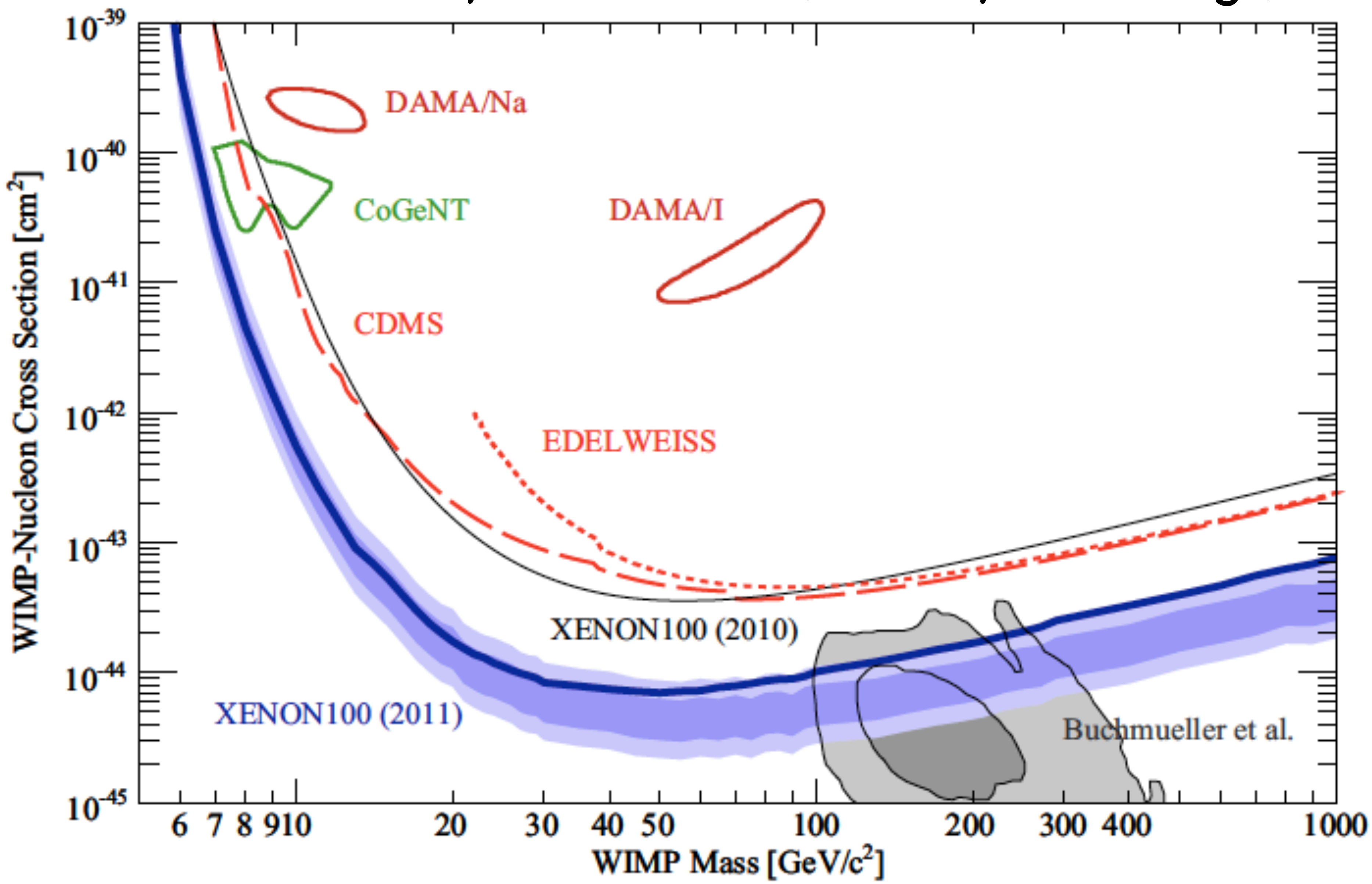
3 events/1.8 backgd

$\sigma_Z(\chi N)$ spin indep. excluded since long time





exclusion by XENON100 (100 days x 48 kgs)



Higgs boson exchange being probed now for $m_h = 125\ GeV$

$$\sigma_h(\chi N) \approx 10^{-43} cm^2 \ (\frac{\lambda}{0.1})^2 (\frac{100GeV}{m_\chi})^2 (\frac{100GeV}{m_h})^4$$

Conclusion (no lack of ? marks)

1. Natural or unnatural theories?

before accepting a shift of paradigm,
useful to be patient and careful (but courageous as well)

2. One or more Higgs bosons?

could be the lightest new particle(s) around
need a better exp ⇔ theory communication

3. What about the flavour puzzle?

$m's, V_{CKM} \Leftrightarrow \lambda_{ij}^{Yukawa}$: a great embarrassment,
unlikely to be solved without much needed key data

4. The Multiverse?

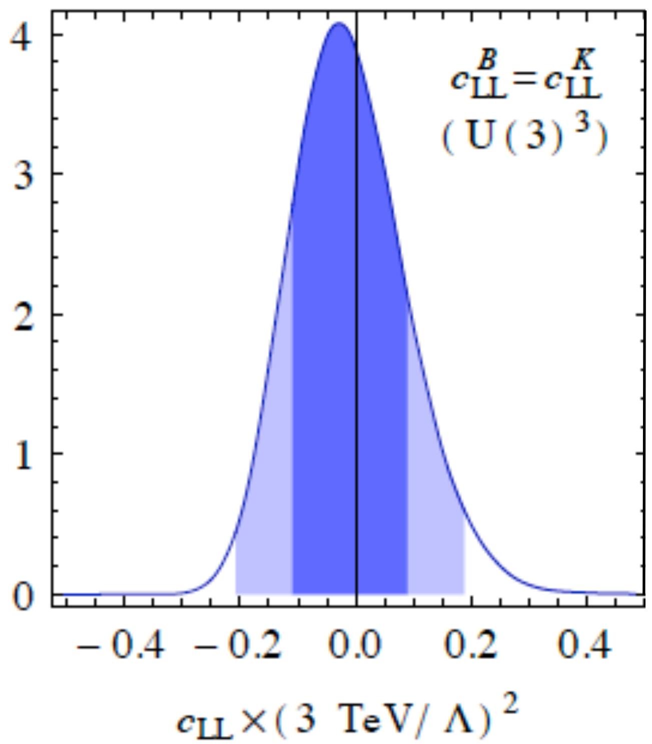
Yes, perhaps, but then what?

The $\Delta F = 2$ case

$U(3)^3$

$$\frac{c_{LL}}{\Lambda^2}\xi_{ij}^2\frac{1}{2}(\bar{d}_{Li}\gamma_\mu d_{Lj})^2$$

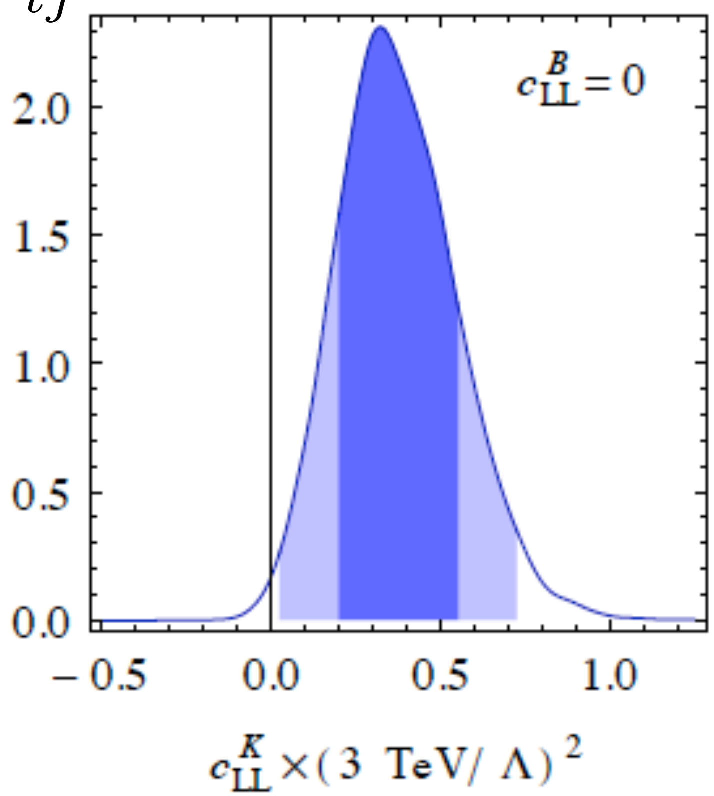
$$\xi_{ij} = V_{ti}V_{tj}^*$$

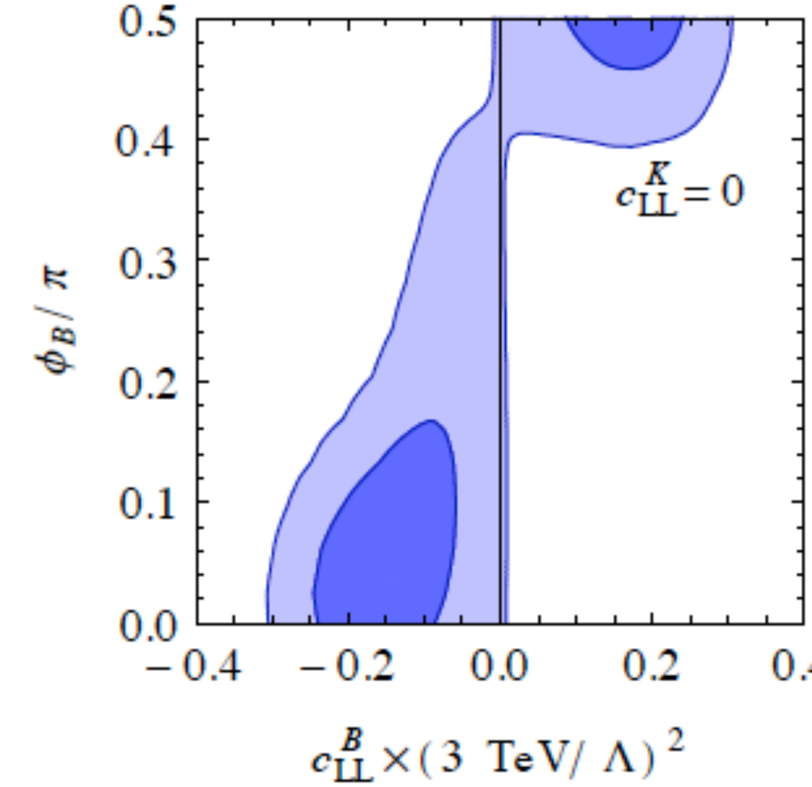


(cannot fit the "discrepancy")

$U(2)^3$

$$\frac{c_{LL}^K}{\Lambda^2}\xi_{ds}^2\frac{1}{2}(\bar{d}_{L}\gamma_\mu s_{L})^2 \qquad \frac{c_{LL}^B e^{i\phi_B}}{\Lambda^2}\xi_{ib}^2\frac{1}{2}(\bar{d}_{Li}\gamma_\mu b_{L})^2$$





B, Buttazzo et al 2011 (general, $U(2)^3$)

Flavour tests versus direct searches (cum grano salis)

for $c = 1$ $\quad \Lambda \approx 4\pi(m, f)$

E.g. $c \cdot (3\ TeV/\Lambda)^2 \approx 0.1$ means $m, f \approx 0.8\ TeV$

$\Delta F = 1$ Summary

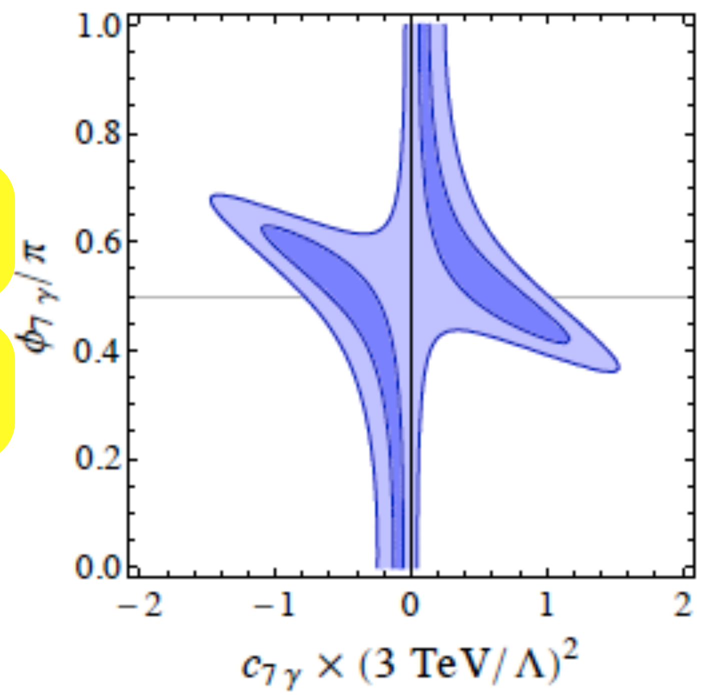
Chirality breaking (cromo-)magnetic operators

$B \to X_{(s,d)}\gamma$

$B \to K(\pi)\mu\mu$

$U(3)^3$

$U(2)^3$



Anarchy

$B \to X_{(s,d)}\gamma$ $\quad \mathcal{A}_{CP}^{direct}(D)$

$B \to K(\pi)\mu\mu$ $\quad \epsilon'/\epsilon$

$f \gtrsim 1\ TeV$

Chirality conserving op.s

$B \to X_{(s,d)}\gamma$

$B \to K(\pi)\mu\mu$

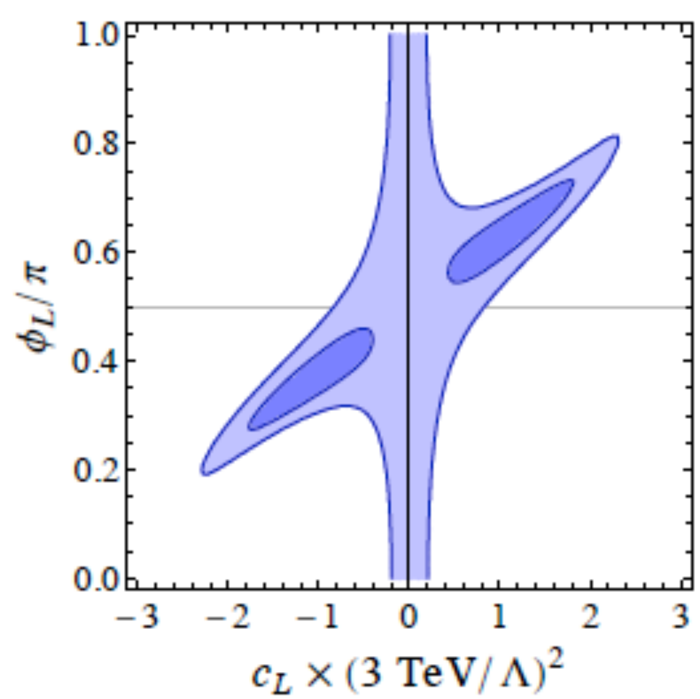
$B_s \to \mu\mu$

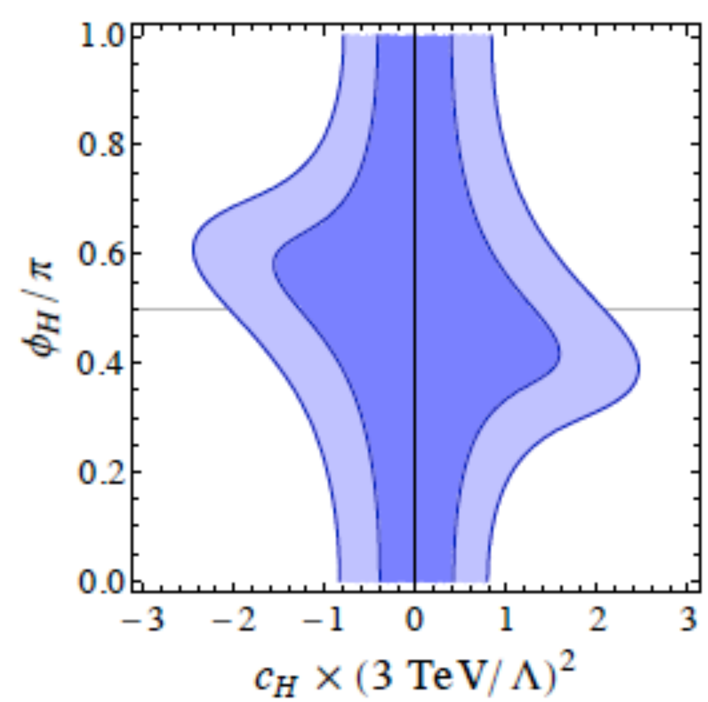
$[K \to \pi\nu\nu]$

} correlated

no phase in $U(3)^3$

$U(2)^3$





NMSSM $\Delta f = \lambda H_u H_d$

Fayet 1975

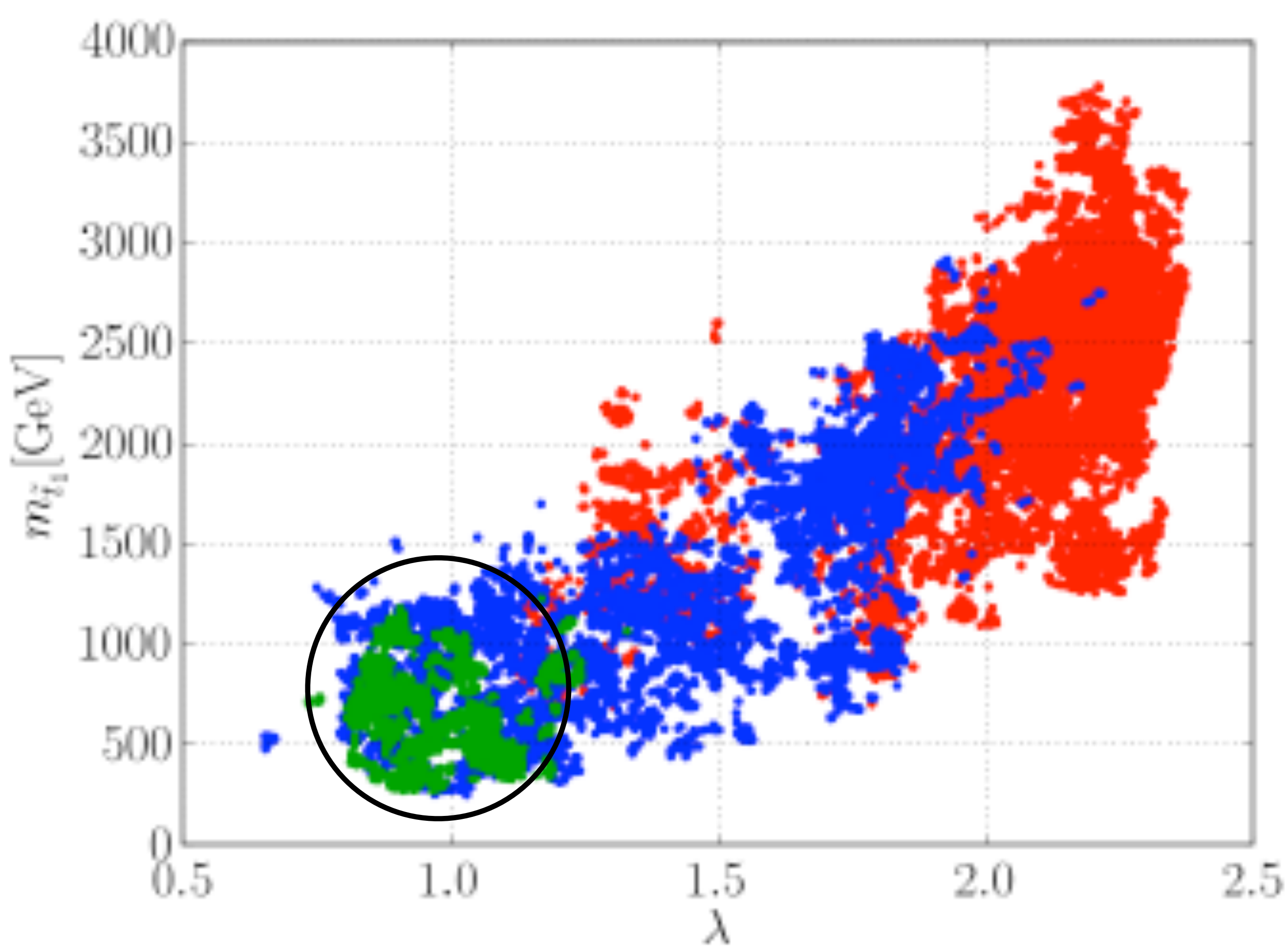
Two independent reasons to consider it:

1. Add an extra contribution to $m_{hh}^2 = m_Z^2 c_{2\beta}^2 + \Delta_t^2 + \lambda^2 v^2 s_{2\beta}^2$ thus allowing for lighter stops

2. Alleviates fine tuning in v for $\lambda \approx 1$ and moderate $\tan\beta$

$$\frac{dv^2}{dm_{H_u}^2}|_{NMSSM} \approx \frac{1}{\lambda^2} \quad \text{versus} \quad \frac{dv^2}{dm_{H_u}^2}|_{MSSM} \approx \frac{4}{g^2}$$

B, Hall, Nomura, Rychkov 2007



green points have better than 5% "combined" fine-tuning and $\Lambda_{mess} = 20\ TeV$ in the scale invariant NMSSM

$$m_{\tilde{t}_1} < 1.2\ TeV$$

$$m_{\tilde{g}} < 3\ TeV$$

Gherghetta et al 2012