LHC “Highlights”

“Pontecorvo 100”
Pisa, September 18-20, 2013

Riccardo Barbieri
SNS and INFN, Pisa

The outcome of the first LHC phase

1. A very major discovery: the/a Higgs boson

   not unexpected

2. No production of new particle, nor of any other new phenomena

   definitely unexpected

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	$\mu(1937)$	$\nu_\mu(1962)$
$t(1994)$	$b(1977)$	$\tau(1975)$	$\nu_\tau(2000)$

$J = 1$ $\quad G^a_\mu(1978) \quad A_\mu(1905) \quad W_\mu(1983) \quad Z_\mu(1983)$

$J = 0$ $\quad h(2012)$

Overview of Coupling Properties Analyses

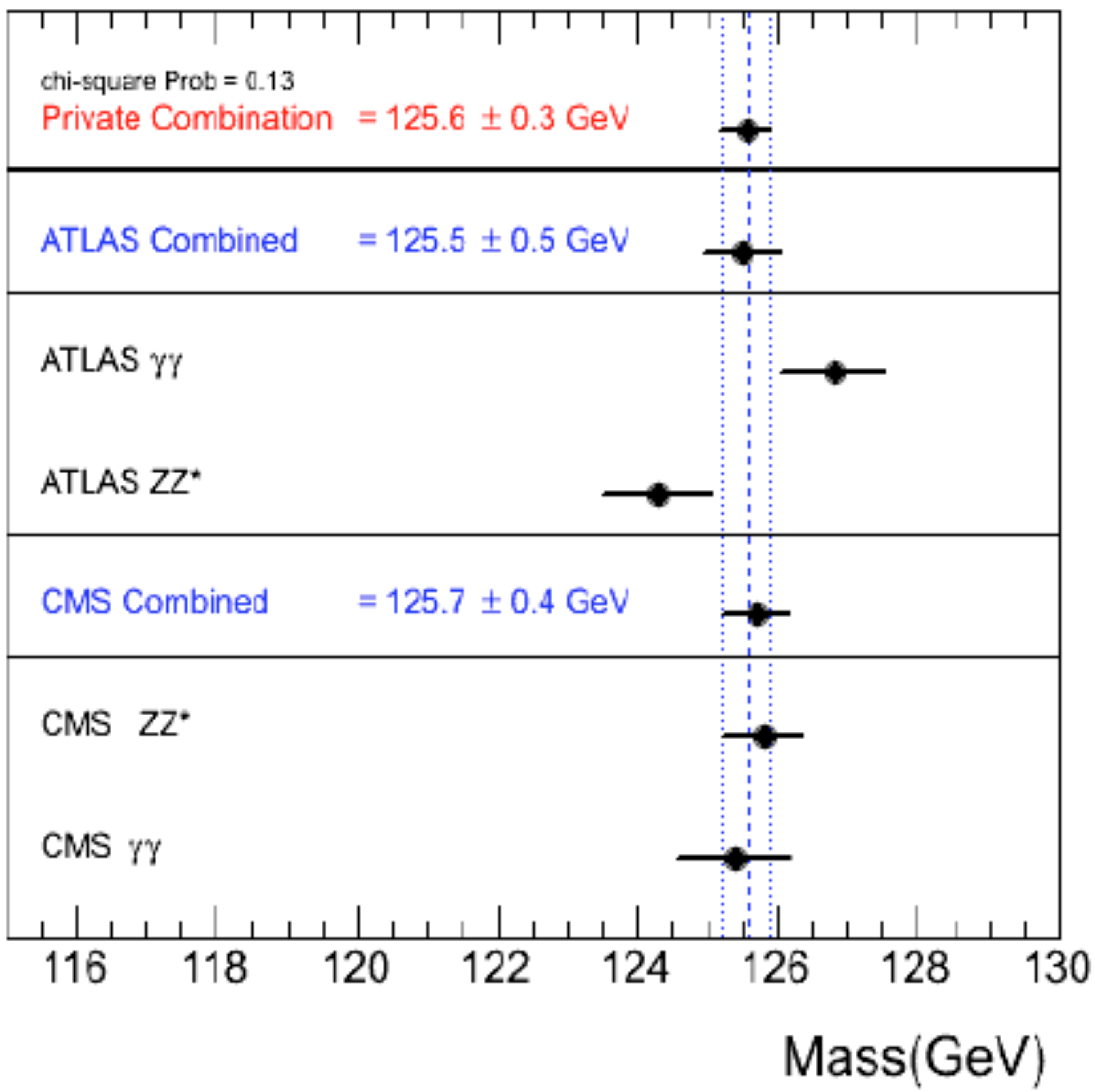
Channel categories	ATLAS				CMS				TeVatron	
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH	VH	ggF
γγ	✓	✓	✓		✓	✓	✓	✓	(inclusive) ✓	
ZZ (llll)	✓	✓			✓	✓			✓	
WW (lνlν)	✓	✓	✓		✓	✓	✓		✓	✓
ττ	✓	✓	✓		✓	✓	✓		✓	
H (bb)			✓	✓		✓	✓	✓	✓	
Zγ	(inclusive) ✓				✓					
μμ	(inclusive) ✓									
Invisible			✓							

✓ Channels studied at LHC so far

✓ Results completed with full run I luminosity

Marumi Kado, GGI, July 2013

Mass measurements in most sensitive channels

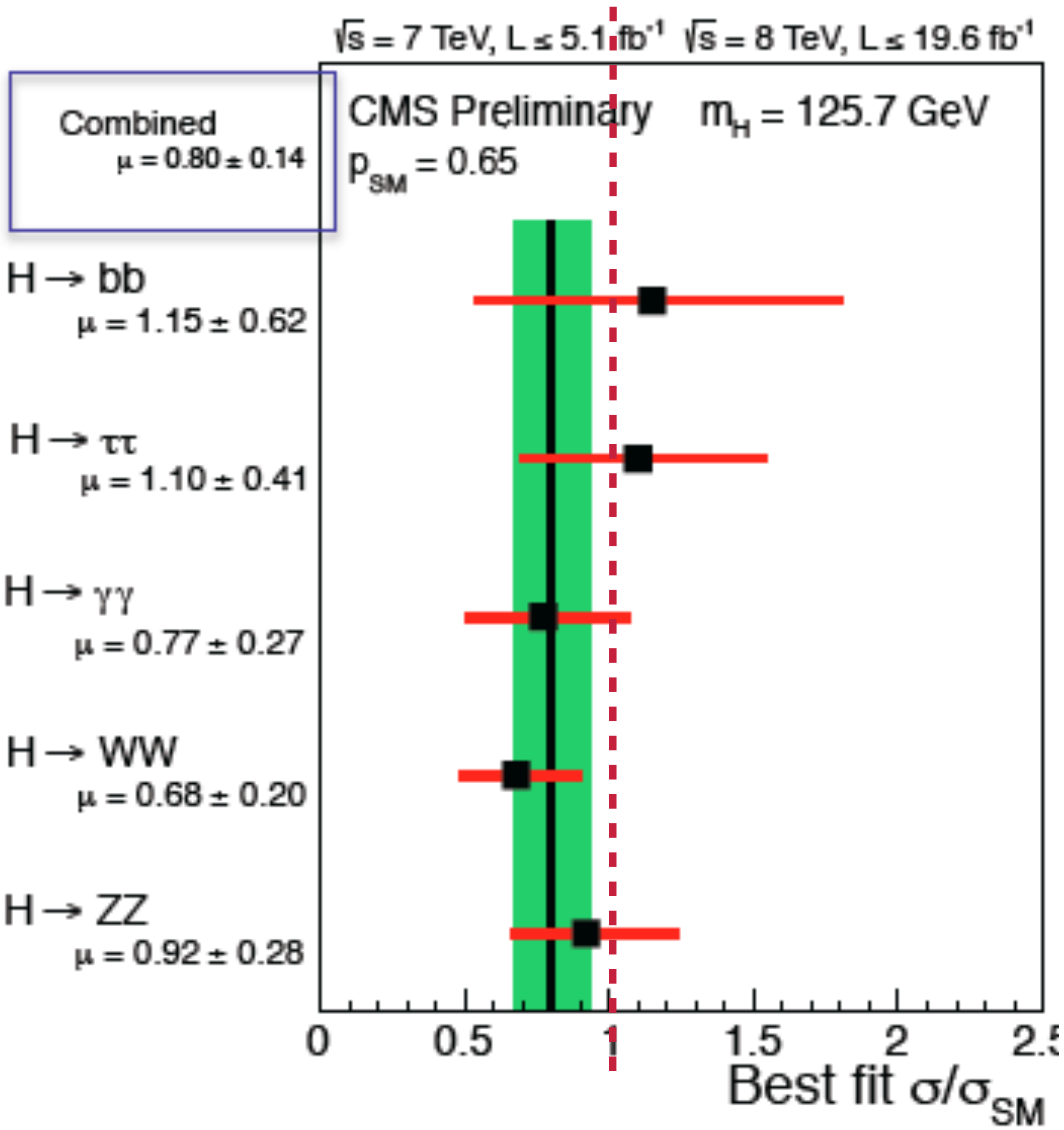


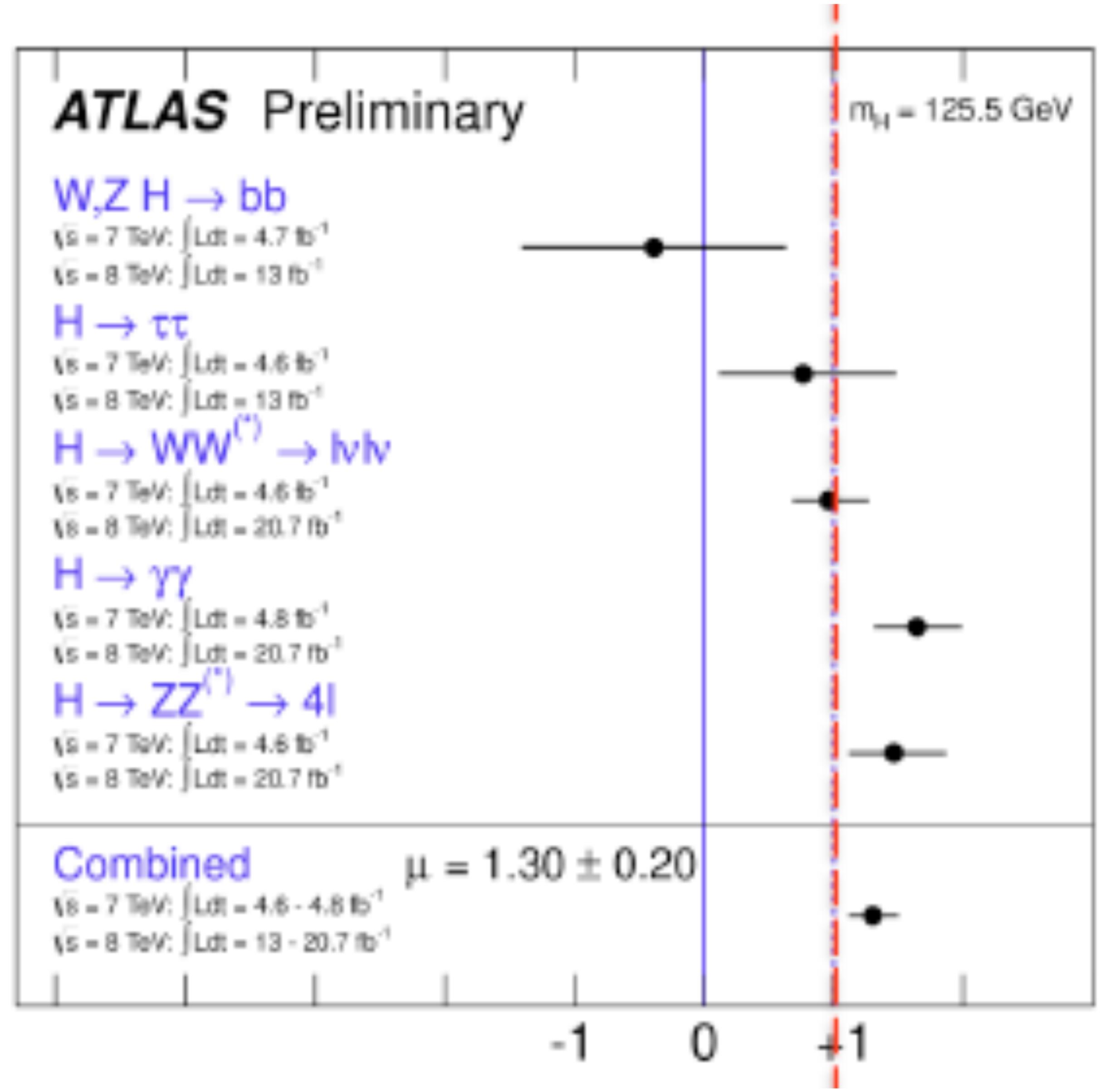
Unofficial combination

χ^2 Probability of 13%

Final word on mass and m from both ATLAS and CMS will require final Run I calibration

Coupling strengths, normalized to SM

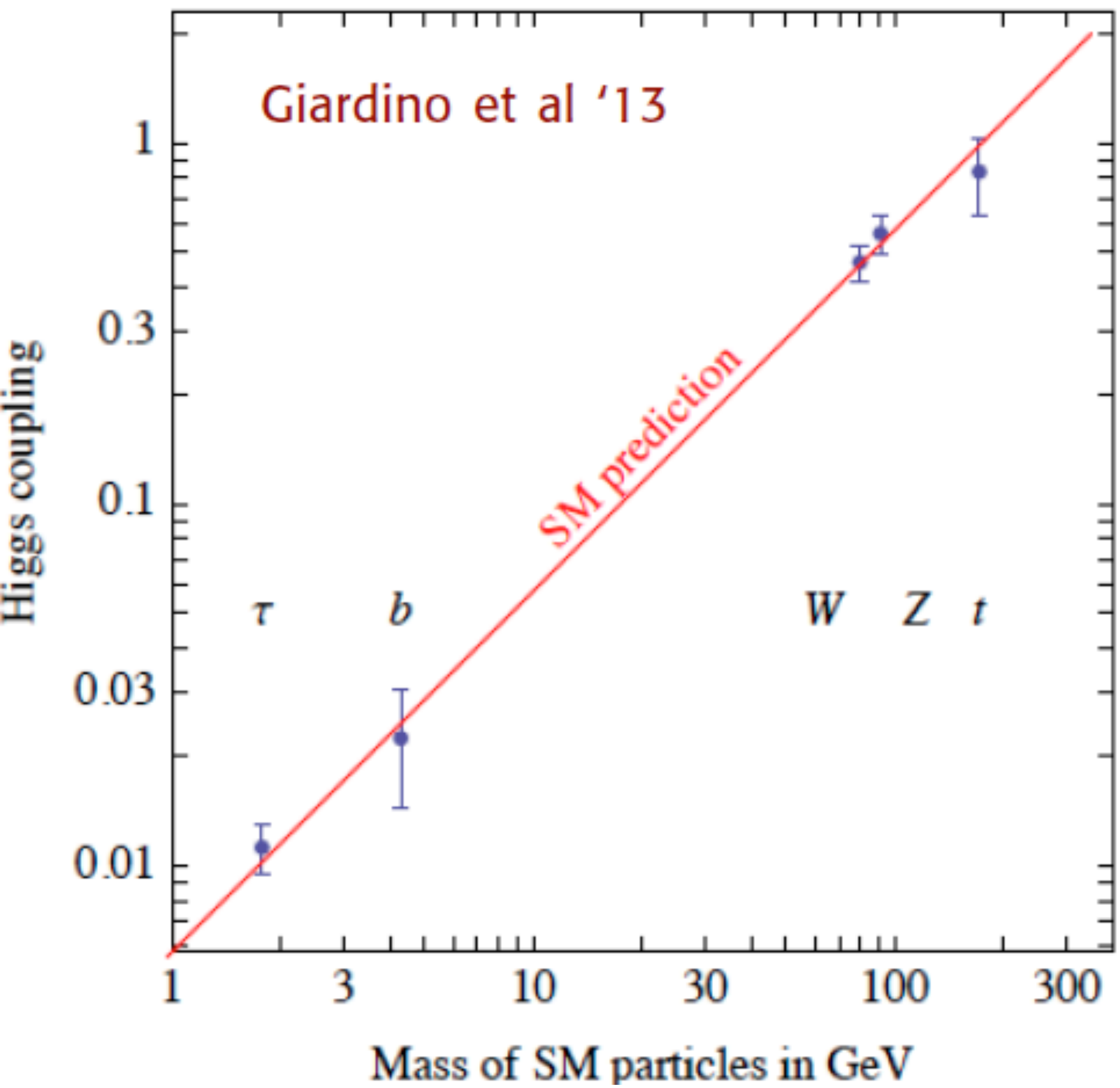




Combined: $\mu = 0.80 \pm 0.14$ $\mu = 1.30 \pm 0.20$

The couplings to other particles

From a theorist's informal combination of ATLAS&CMS data



Giardino, Kannike, Masina, Raidal, Strumia
(as many others)

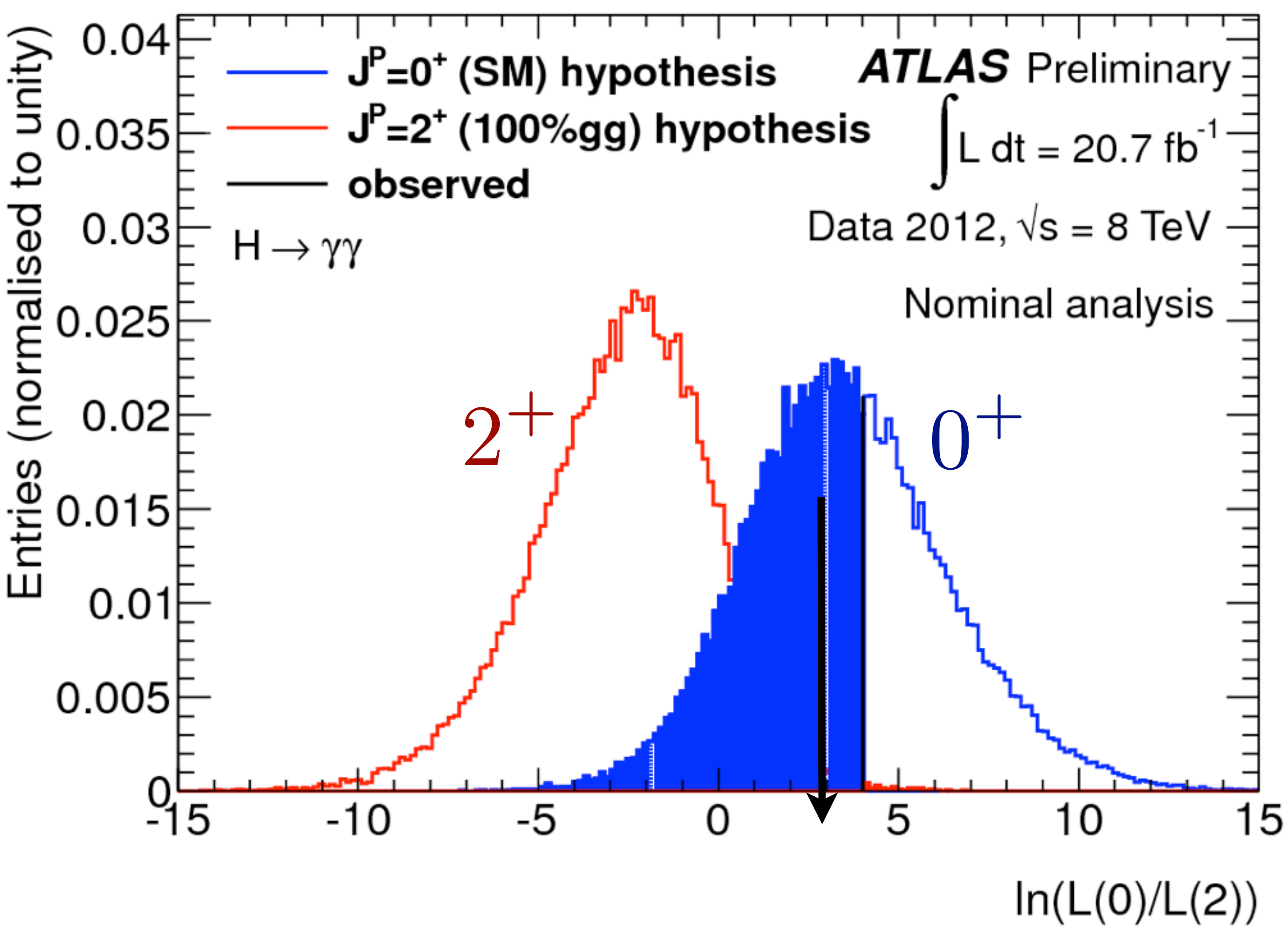
The coupling-versus-mass linear relation is an absolute prediction of the ST
(not exhaustive: $gg, \gamma\gamma$)

No Clebsch distorsion: the Higgs boson is (close to) a doublet

$J^P = ?$ (0^+ expected)

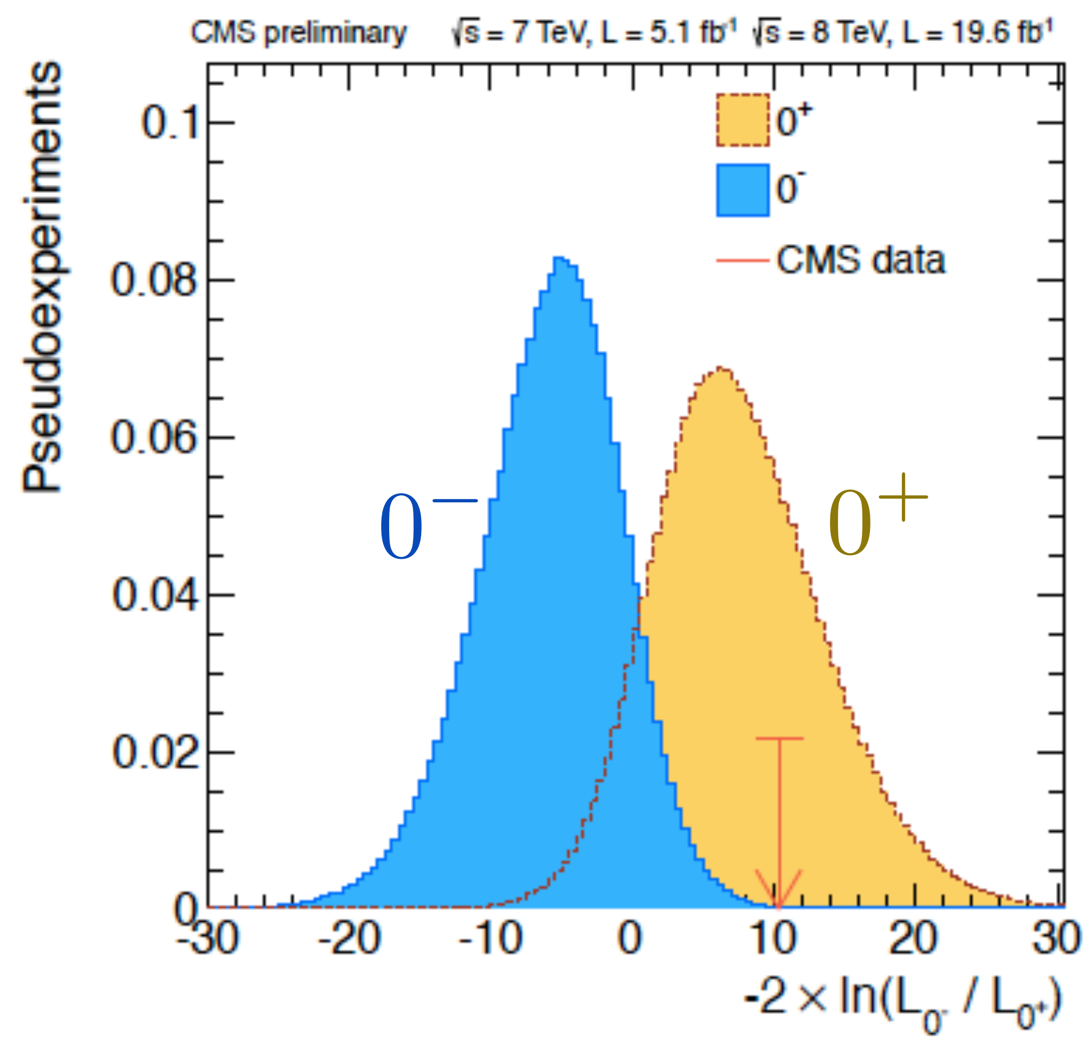
Parity and angular momentum discrimination by angular distribution in decays (pairwise hypothesis tests)

$h \to \gamma\gamma$



the angular momentum looks right

$h \to ZZ^* \to 4l$



the parity looks right

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?

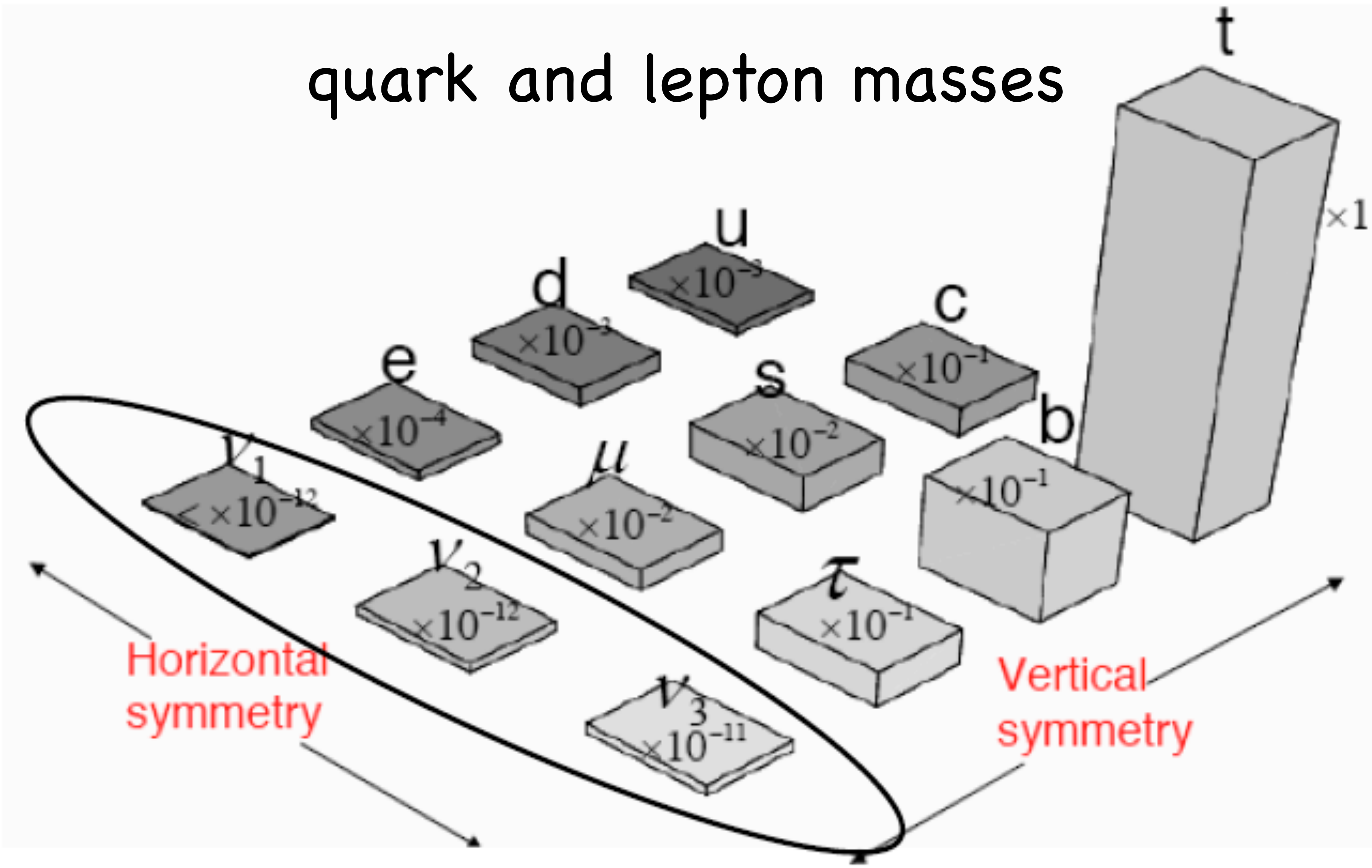
which dynamics, if any?

how about the flavour puzzle?

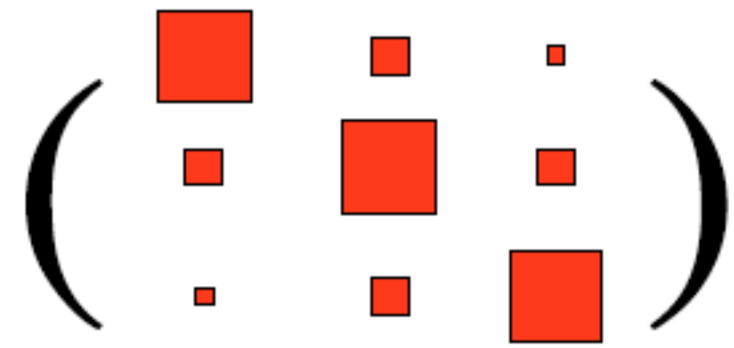
(Note: no physical inconsistency!)

[Dark Matter, Baryon asymmetry]

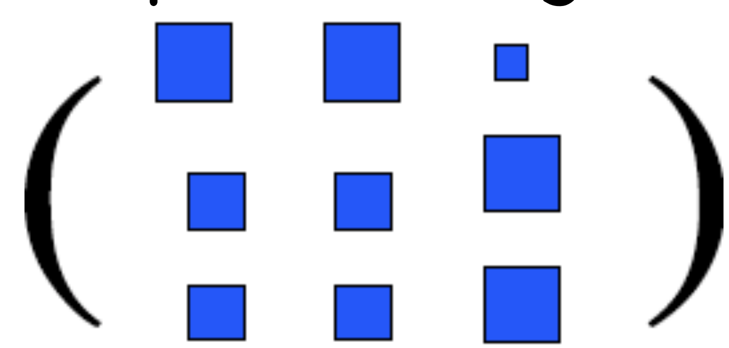
The flavour puzzle $\lambda_{ij}\Psi_i\Psi_j h$



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

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

The Cabibbo-Kobayashi-Maskawa picture works fine

A possible interpretation: $\Lambda_f \gtrsim 10^4 \div 10^5\ TeV$
Not a necessity, nor the most interesting case

An underlying flavour symmetry, suitable broken, may lead to a quasi-CKM picture with 20-30% deviations compatible with current data

To search for such deviations is both very important *per se* and complementary to direct serches for new particles carrying flavour indices (squarks, etc)

Similar considerations apply to the leptons: $\mu \to e + \gamma$

About naturalness

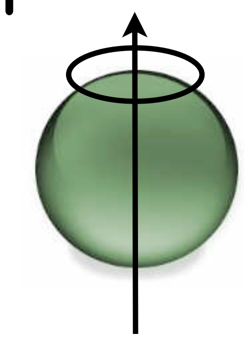
a dominant paradigm in the last thirty years

It is possible to do physics at different scales without knowing the (accidental) details of what happens at shorter distances

Atomic physics	Nuclear physics	EW physics	? physics	gravity

The classical electron self energy

Among the many examples that have worked so far:

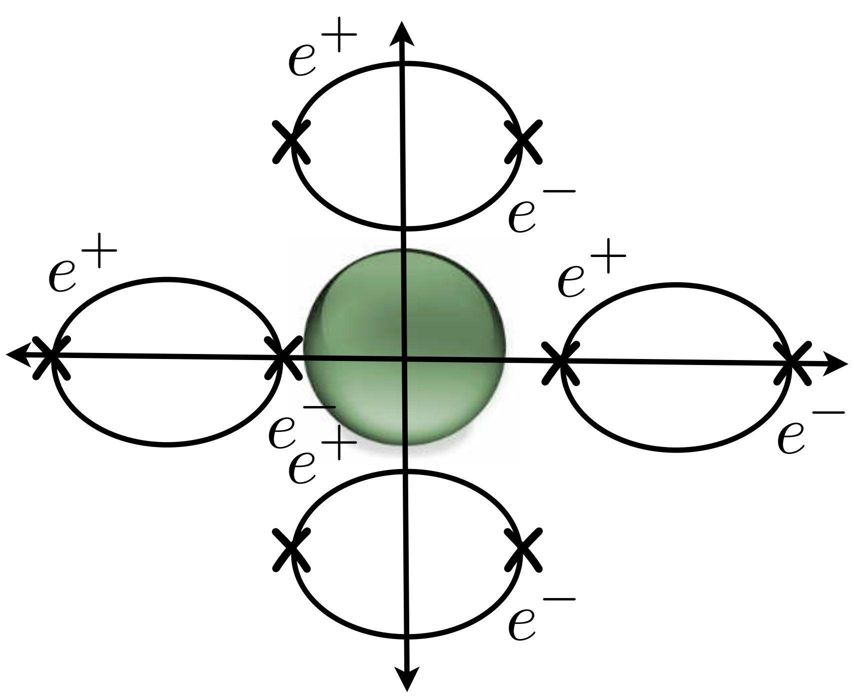


Weisskopf 1939

electric $E_{el} \approx \frac{e^2}{r_e} \lesssim m_e c^2 \;\Rightarrow\; \Lambda_e \equiv \frac{\hbar}{r_e c} \lesssim \frac{m_e}{\alpha} \approx 70\ MeV$

magnetic $E_{mag} \approx \frac{\mu^2}{r_e^3} \lesssim m_e c^2 \;\Rightarrow\; \Lambda_e \lesssim \frac{m_e}{\alpha^{1/3}} \approx 3\ MeV \quad (\mu = \frac{e\hbar}{2m_e c})$

the positron (a doubling of the d.o.f. at $\Lambda_e \sim m_e$) solves the problem



$(M^2_{\pi^+} - M^2_{\pi^0} \;\Rightarrow m_\rho \lesssim 800\ MeV)$

$(M_{K^0_L} - M_{K^0_S} \;\Rightarrow m_c \lesssim 2\ GeV)$

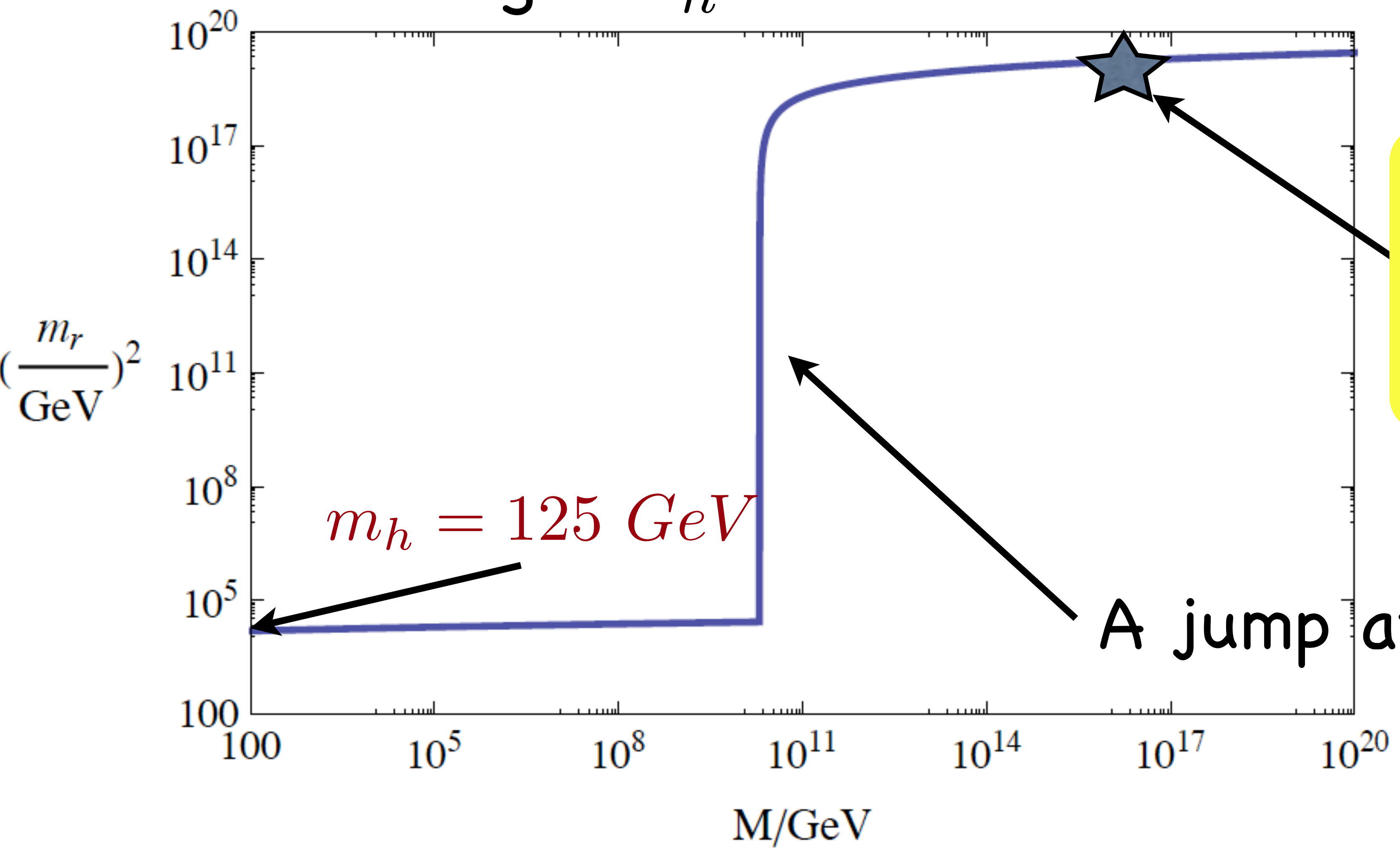
The Higgs naturalness (fine-tuning) once again

In the SM: $\delta m_h^2 \approx (125\ GeV)^2 (\frac{\Lambda}{500\ GeV})^2$

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

Take the SM + a particle of mass $M_H = 10^{10}\ GeV$
and coupling λ_H to the Higgs boson

The running m_h^2 versus the scale M



m_h depends on a very precise initial condition at some short distance

A jump at M_H of size $\frac{(\lambda_H M_H)^2}{16\pi^2}$

B, 1996

Three reactions to the Fine Tuning problem

(and to the lack of positive data, so far)

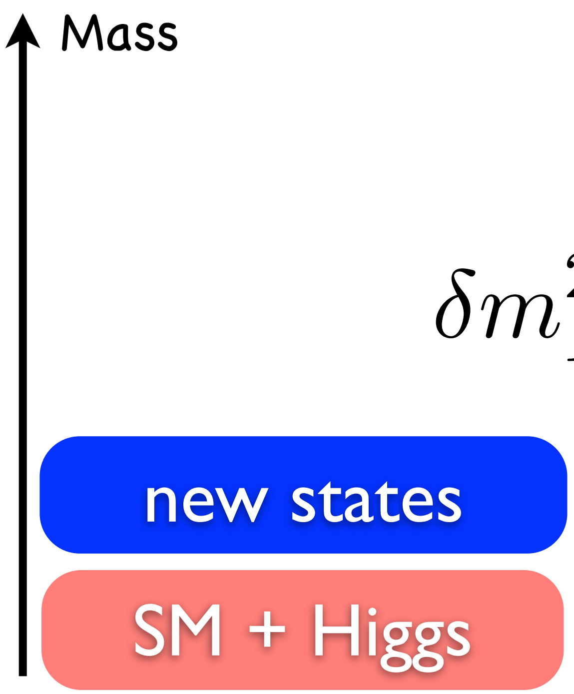
1. Cure it by symmetries (SUSY, Composite Higgs) no matter which short distance physics is there

2. Select (and make assumptions about) the short distance physics

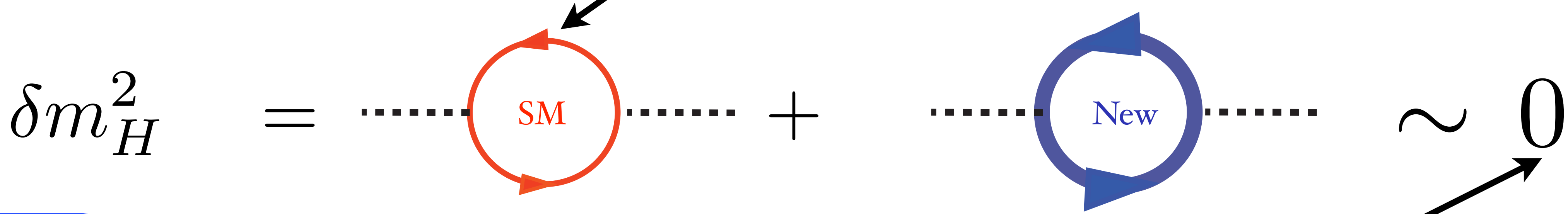
3. Accept it: the multiverse, the 10^{120} vacua of string theory

Anything else?

1. A “natural” Higgs boson by symmetries



mostly the top

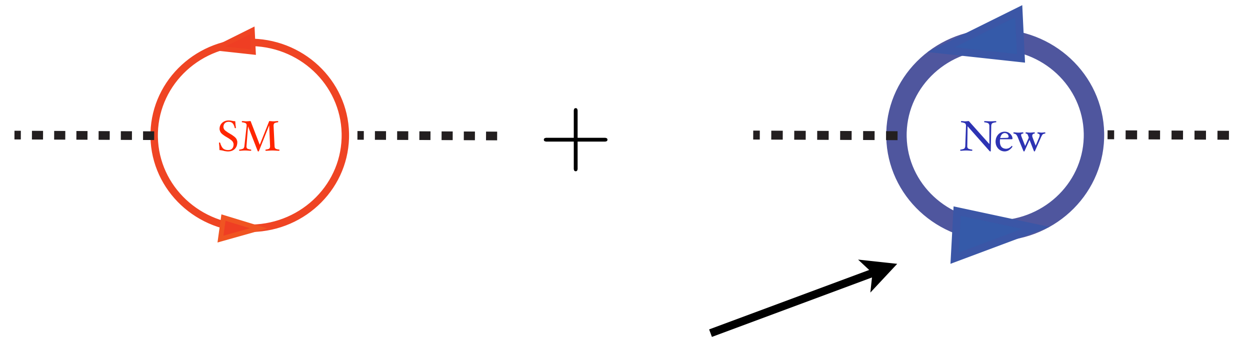


by an (approximate) symmetry

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

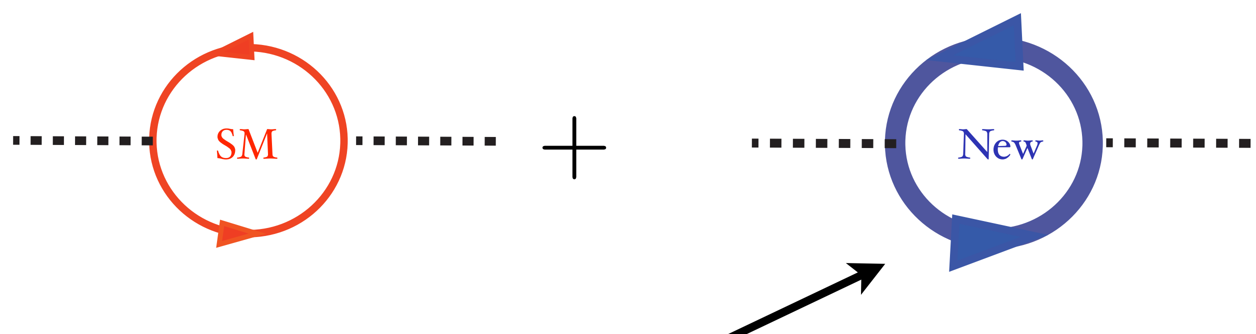
Supersymmetry

$\delta m_H^2 =$  ~ 0

s-particles

The Higgs boson as a pseudoGolsdtone

(like the π in QCD)

$\delta m_H^2 =$  ~ 0

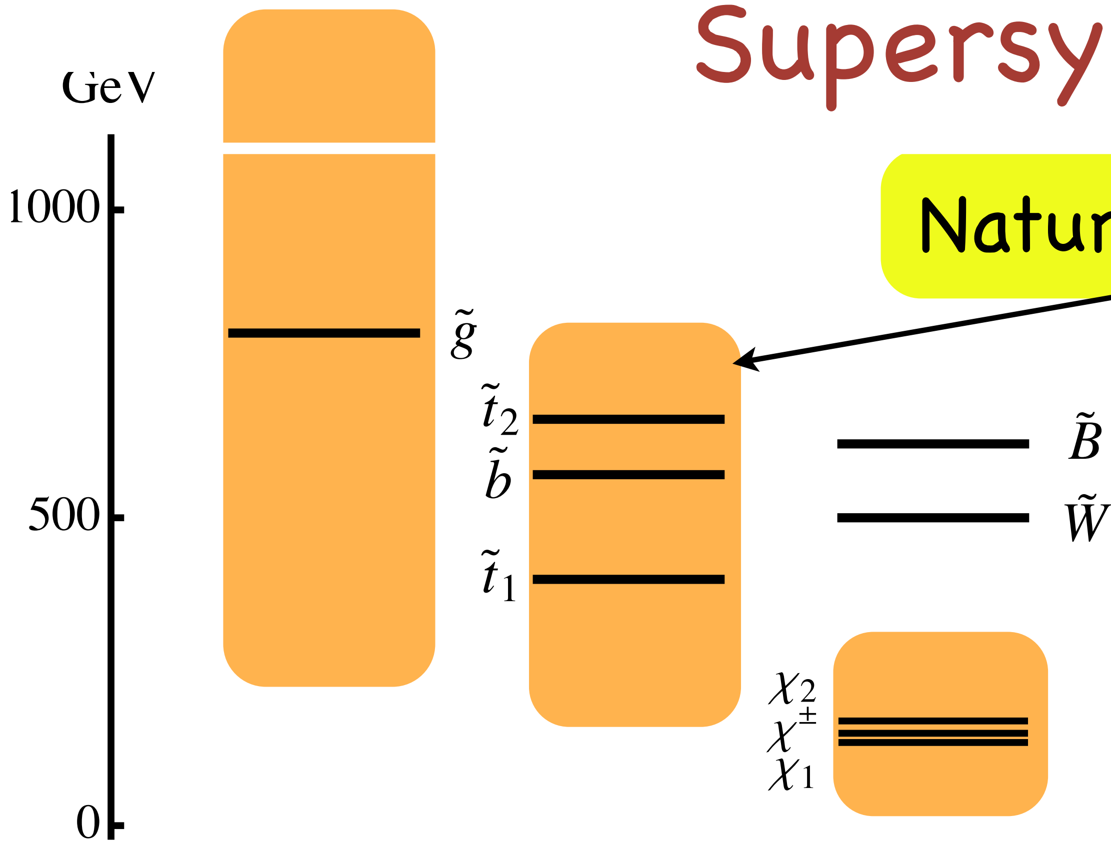
Heavy "composite" fermions

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

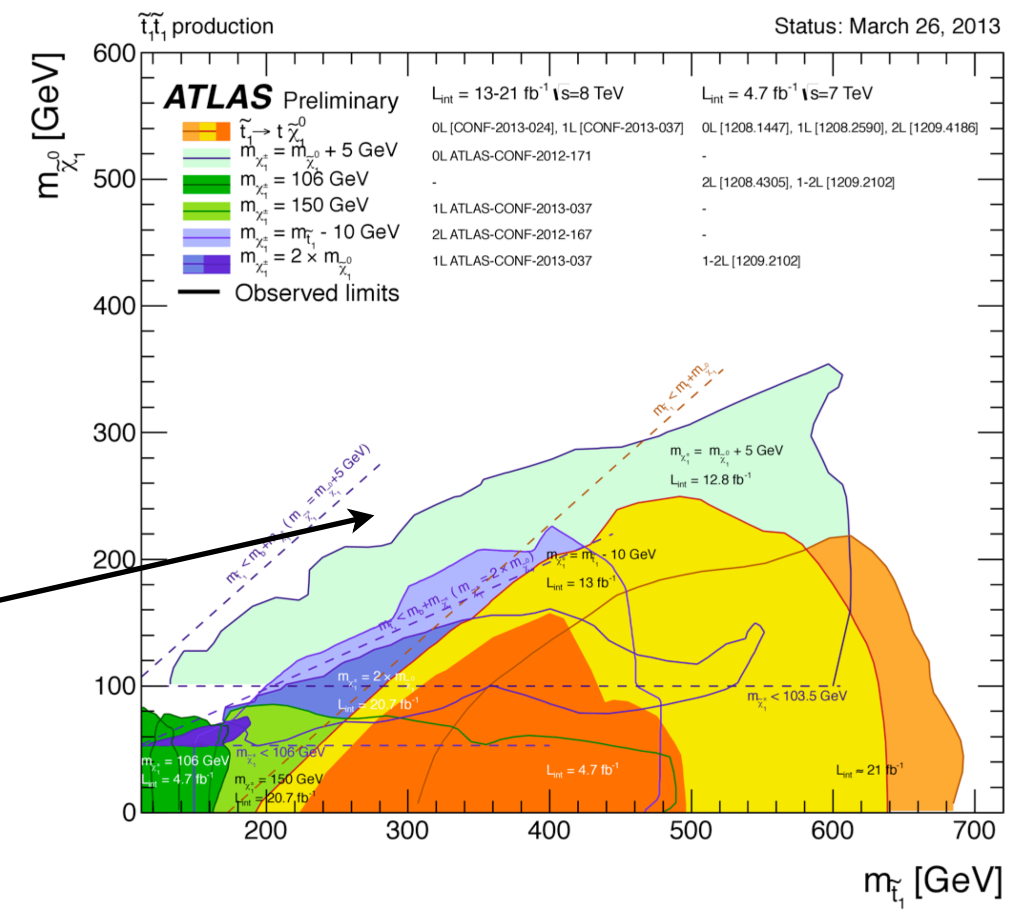
$M_{New} \gtrsim 500 \div 1000\ GeV$

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

Supersymmetry searches



Natural spectra



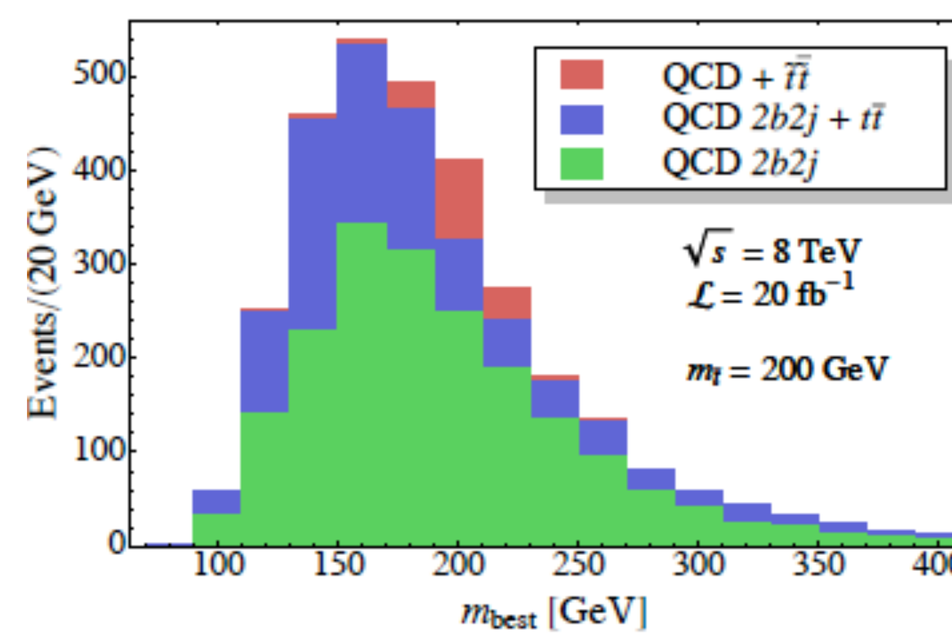
Compressed spectra

RPV in baryons only (with MFV)

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

Csaki et al

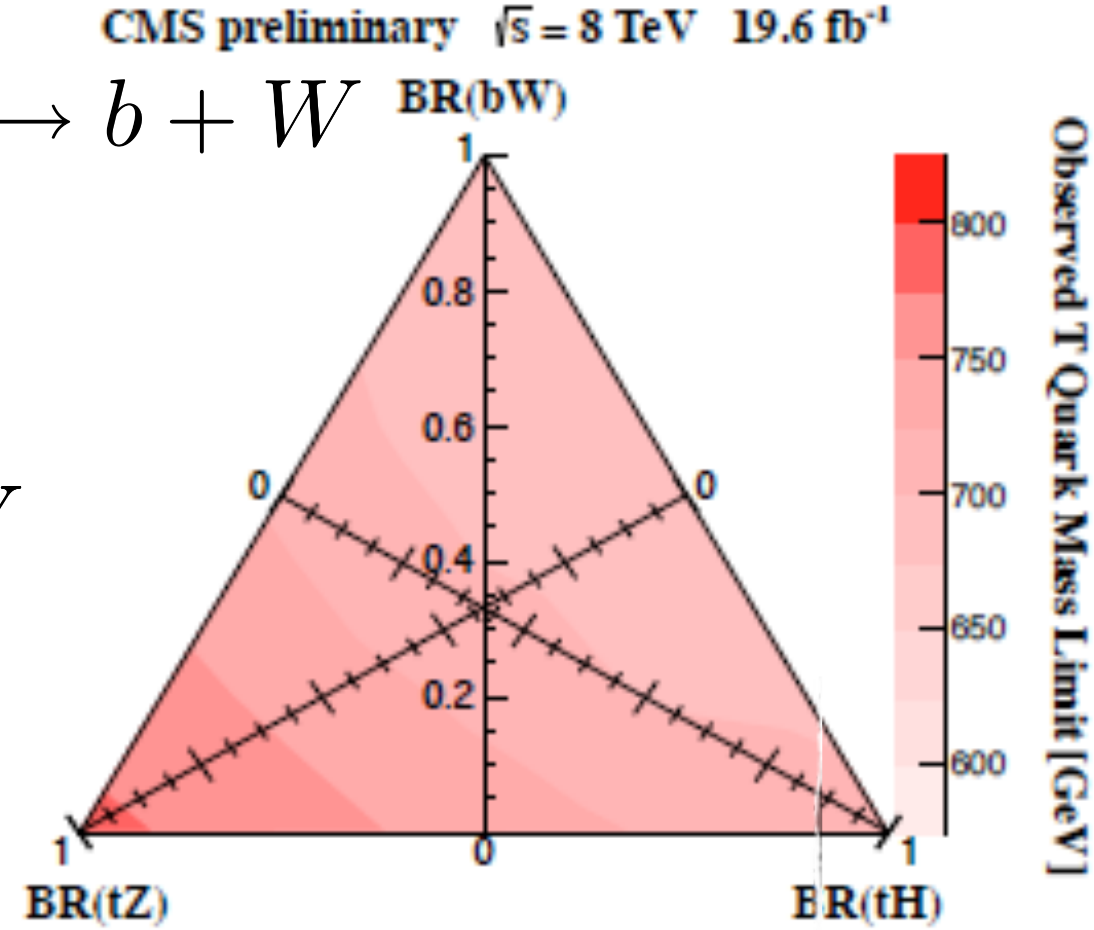
Franceschini, Torre



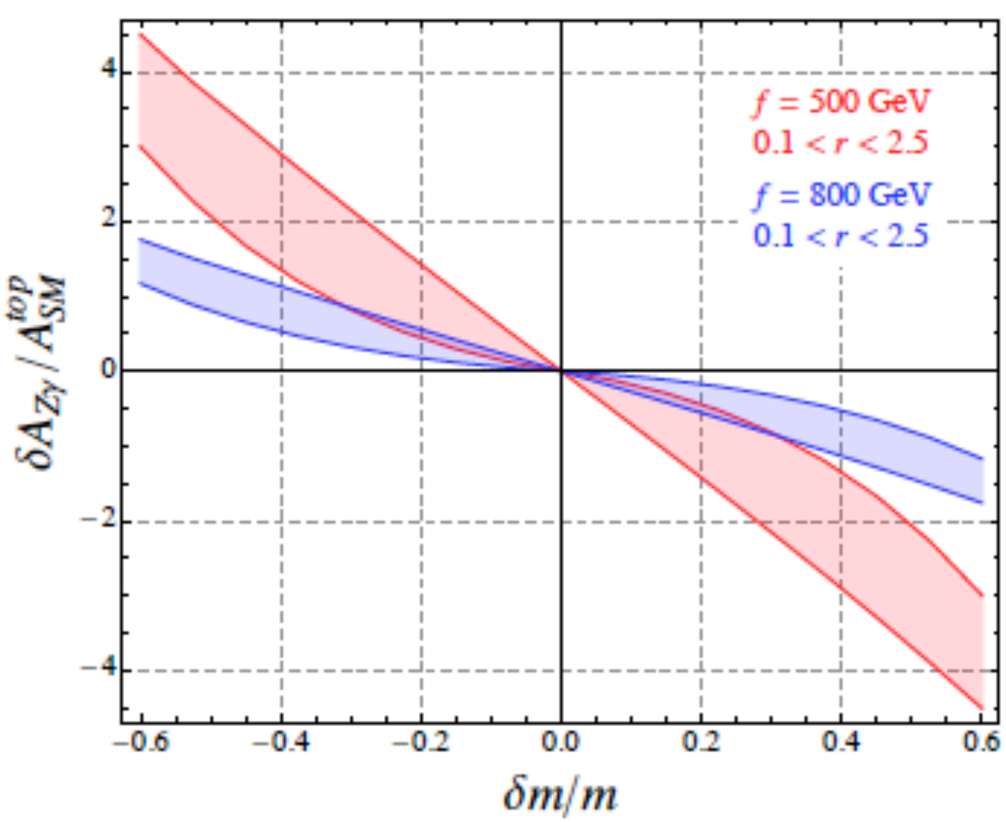
Higgs-as-PGB searches

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

$T \to b + W$



$T \to t + Z$ $T \to t + H$



Indirect searches

$h \to Z\gamma$

Contino et al

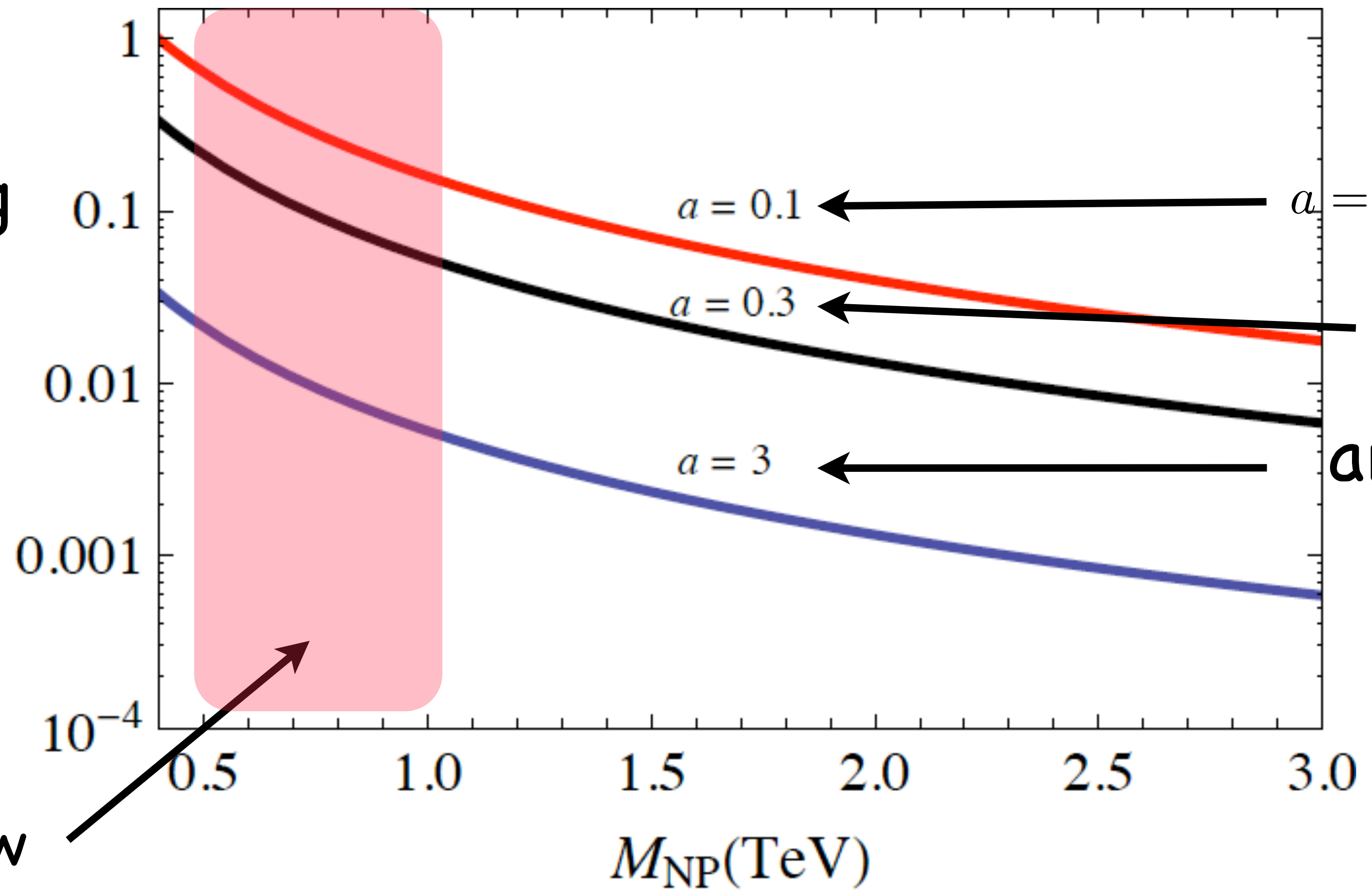
A quantitative measure (!?) of naturalness

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

model dependent

$1/\Delta$ is a measure of fine tuning to accommodate a $\delta m_h^2 > m_h^2$

fine tuning $\frac{1}{\Delta}$



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

some NMSSM

an indicative MSSM

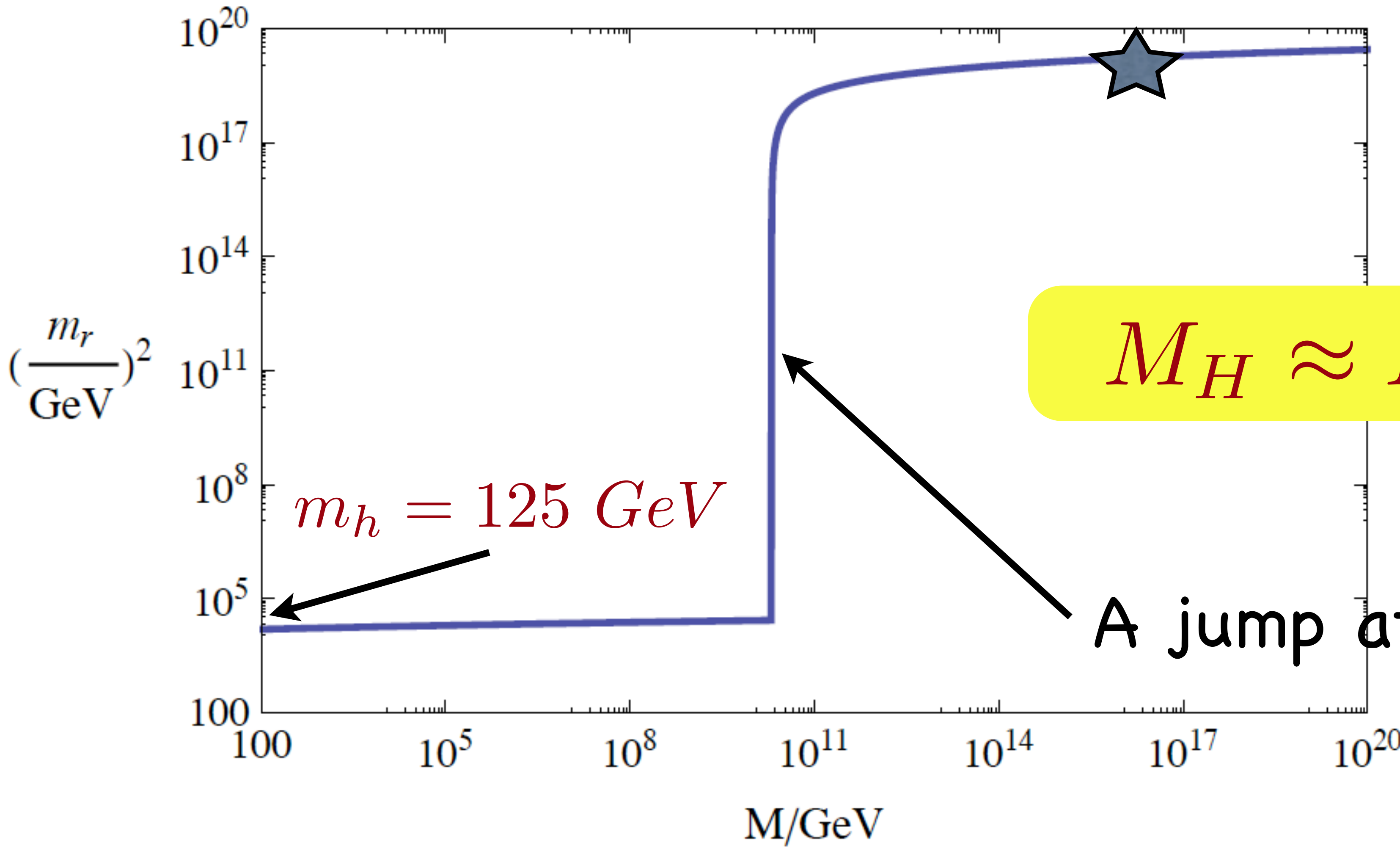
≈ LHC now

Some level of fine tuning there anyhow. How much is tolerable?

LHC14 should see masses (M_{NP}) at least twice as large

2. Select the short distance physics

(and make assumptions about the one we know already)



$M_H \approx M_{Pl}$? $M_H \approx \Lambda_Y$?

A jump at M_H of size $\frac{(\lambda_H M_H)^2}{16\pi^2}$

If one can get around these M_{Pl}, Λ_Y problems, select BSM physics that keeps the jump moderate enough

DM and neutrino masses can, sometimes with signs at LHC

non-SUSY GUTs not compatible with this picture

Shaposnikov et al   Farina, Pappadopulo, Strumia

3. Accept the fine tuning

Weinberg 1989 (when the C.C. was thought to be zero):

"If it is only anthropic considerations that keep the effective Cosmological Constant within empirical limits, then this constant should be rather large, large enough to show up before long in astronomical observations"

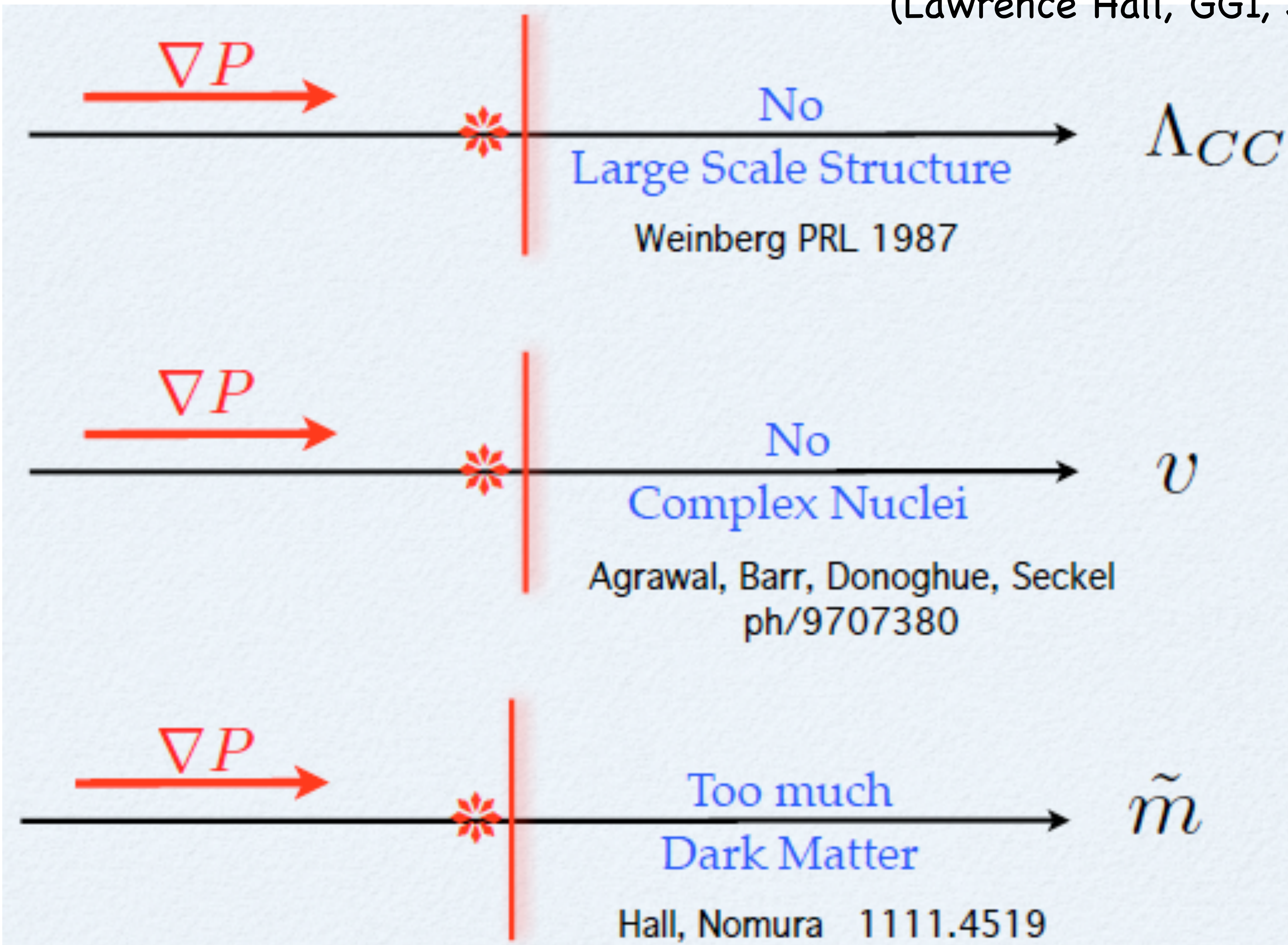
From high z supernovae, in 1998 and later:
the universe in accelerated expansion likely due to a C.C.
more than 10^{120} times small than its natural value M_{Pl}^4

Can the weak scale be fine tuned for similar "environmental" reasons?

A "multiverse", say with $N >> 10^{120}$, almost inevitable

Anthropic pressure

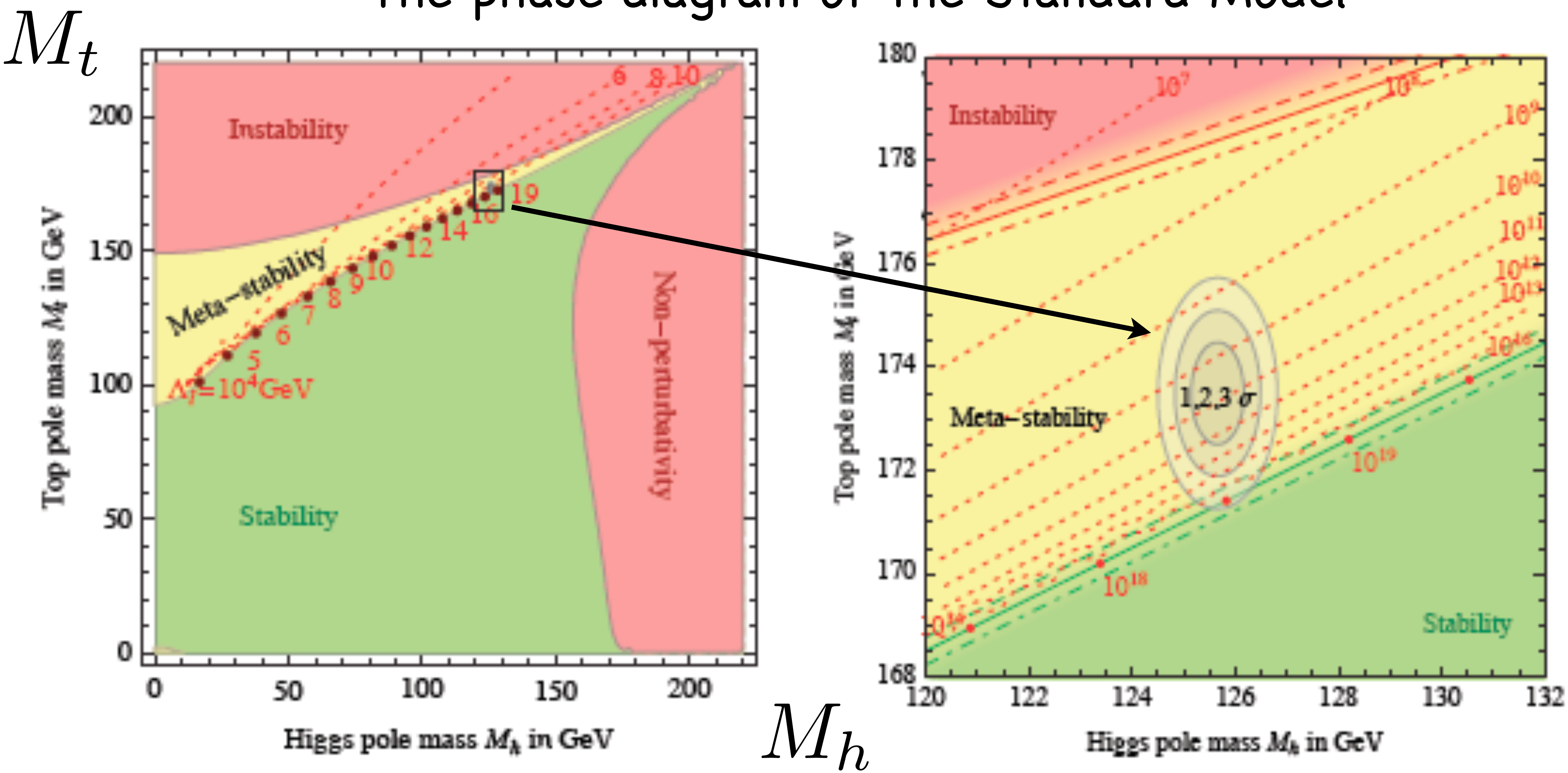
(Lawrence Hall, GGI, July 2013)



If so, a major shift in the way of doing physics !

Assume the ST unchanged up to M_{Pl}

The phase diagram of the Standard Model



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

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

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

A key question for LHC14:

(even independently from naturalness)

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

$SU(2) \times U(1),\ U(1)_{em}$ preserved

$\oplus\ \ SU(2) \times U(1)$ fully broken

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 $pp \to h_{\neq LHC} + X$

$h_{\neq LHC}$ → decay products

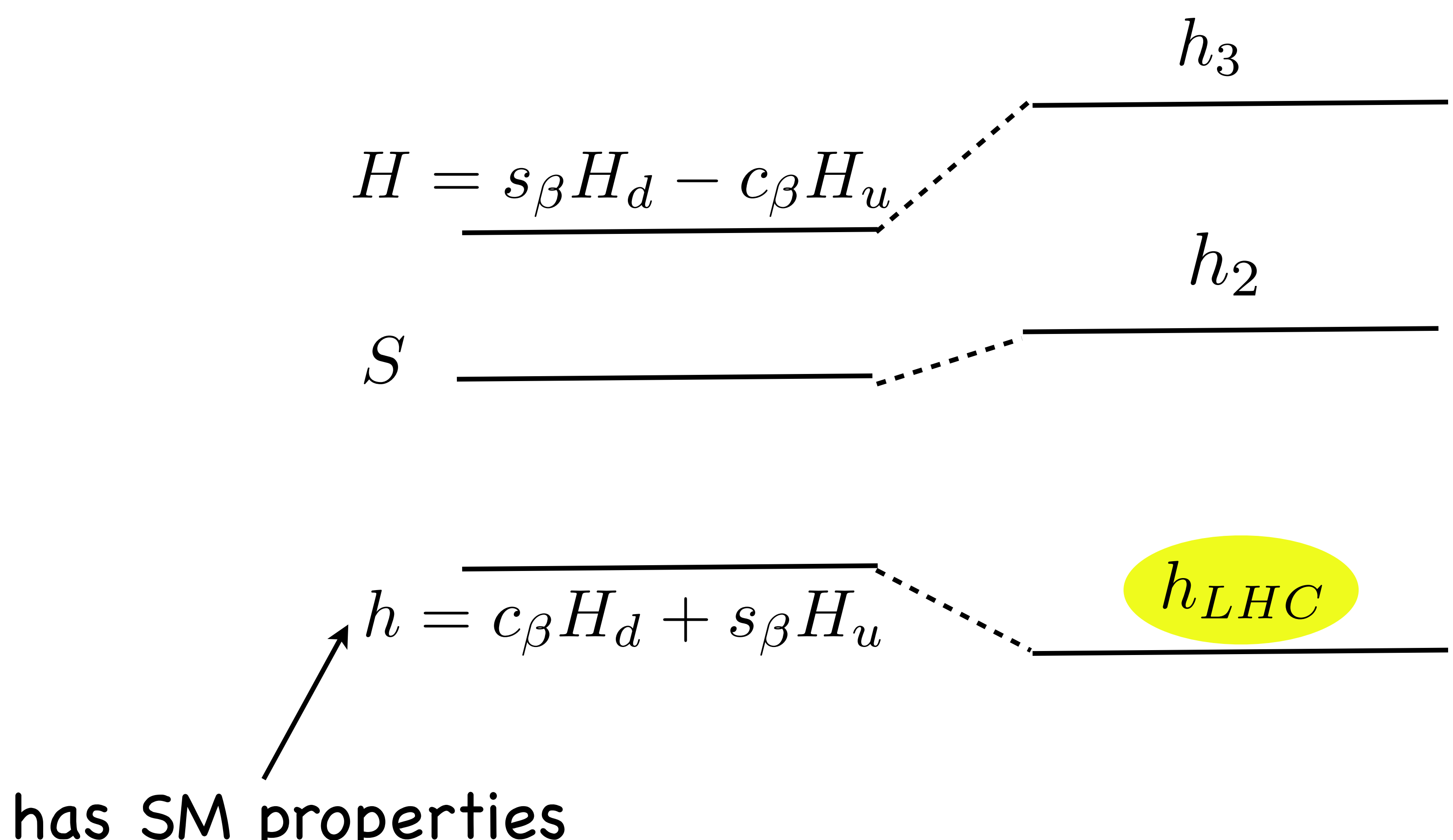
(perhaps itself in the decay products of...)

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

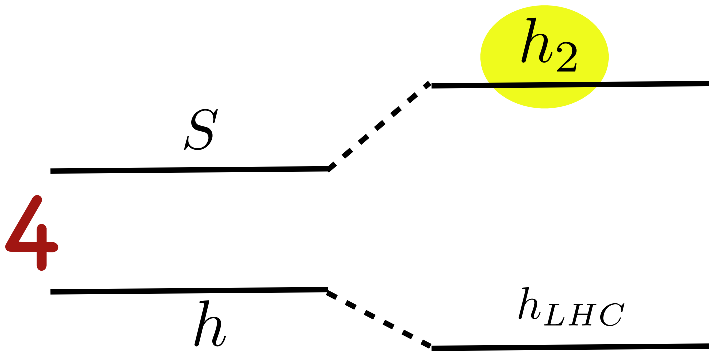
(the NMSSM example)

$\lambda S H_u H_d$

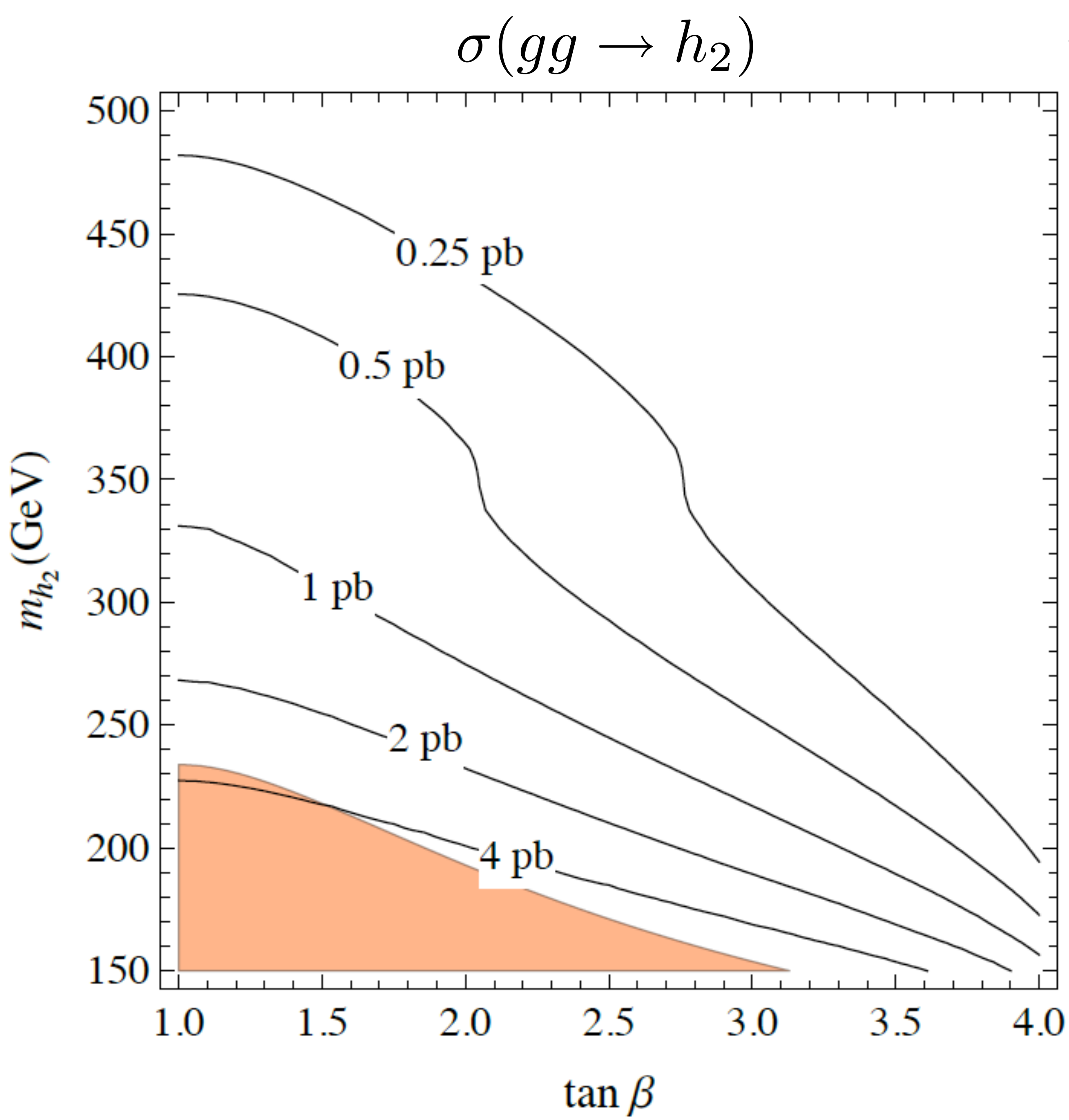
Fayet 1975

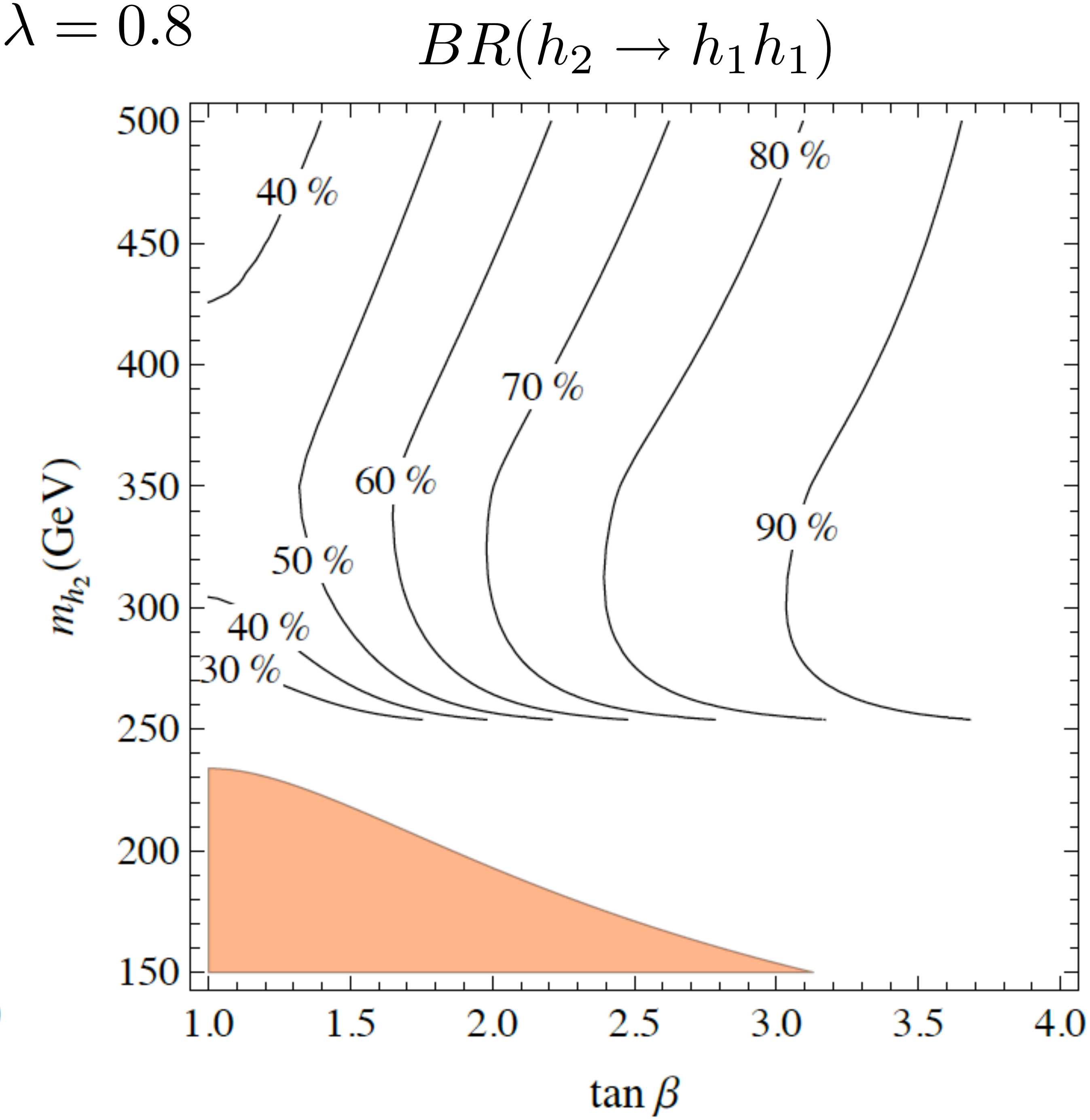


NMSSM: Direct search at LHC14



$\lambda = 0.8$





orange = excluded by h_{LHC} - measurements

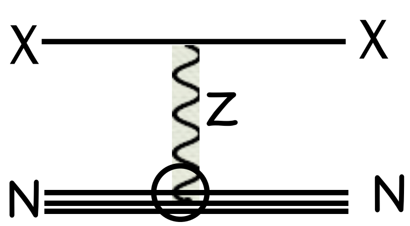
B, Buttazzo, Kannike, Sala, Tesi

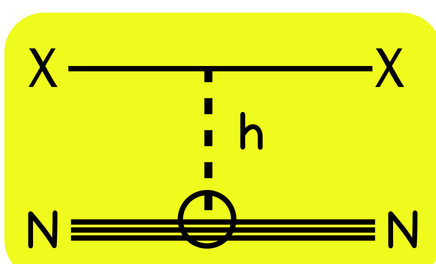
DM searches and the Higgs boson

$$\chi N \rightarrow \chi N$$

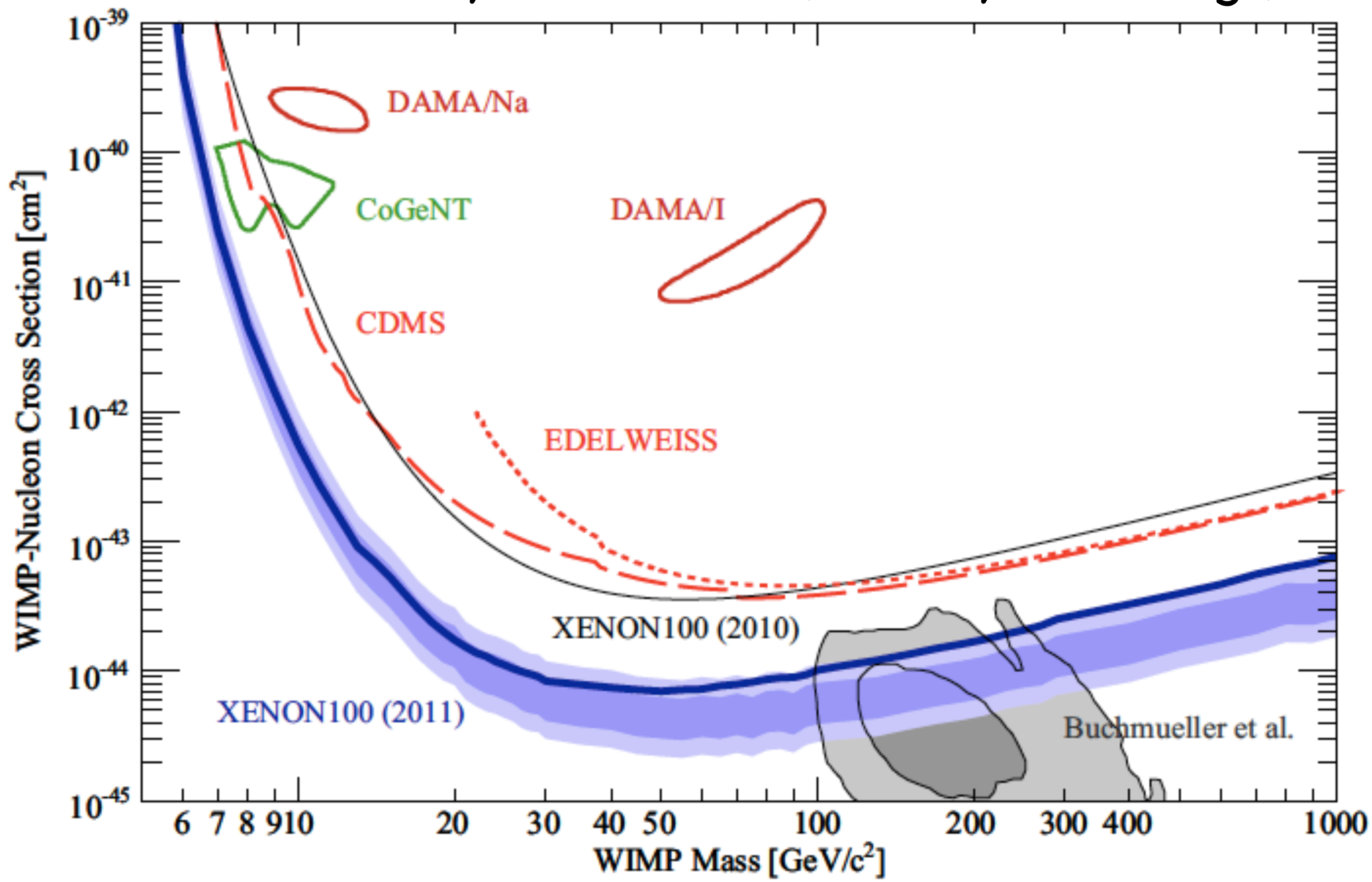
3 events/1.8 backgd

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





exclusion by XENON100 (100 days x 48 kgs)



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

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

Conclusions

1. Naturalness still under scrutiny at LHC14

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

2. The Multiverse?

Yes, perhaps, but then what?

3. One or more Higgs bosons?

could be the lightest new particle(s) around

4. 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

No lack of question marks in the conclusions

A clear lesson from Pontecorvo:
(to us theorists in particular)

Think harder to "unconceivable" ways
to explore new directions

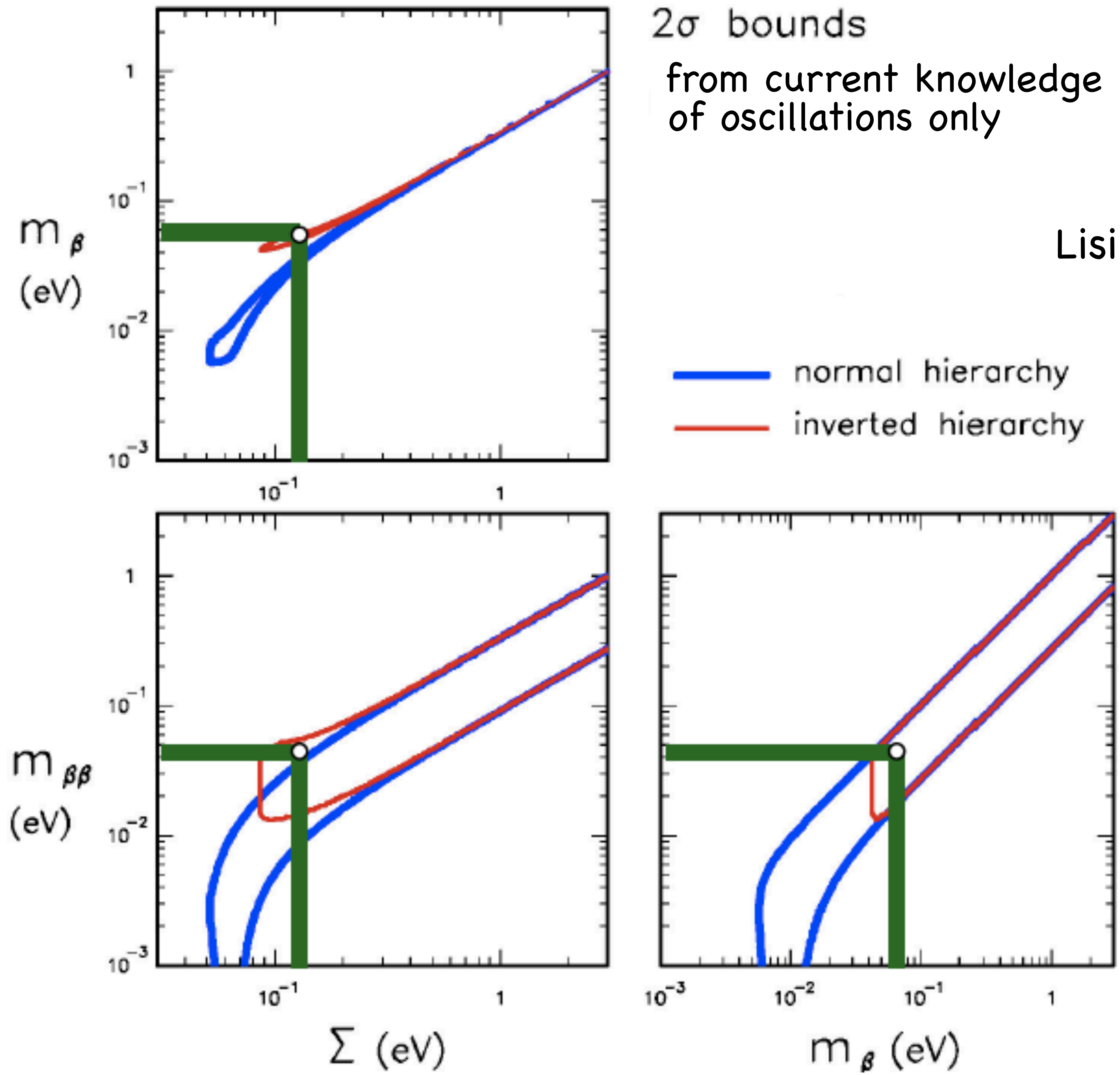
Are there other $\nu + Cl \rightarrow Ar + e$ -type experiments
waiting to be thought of?

Key conceivable measurements

Suppose that at some point:

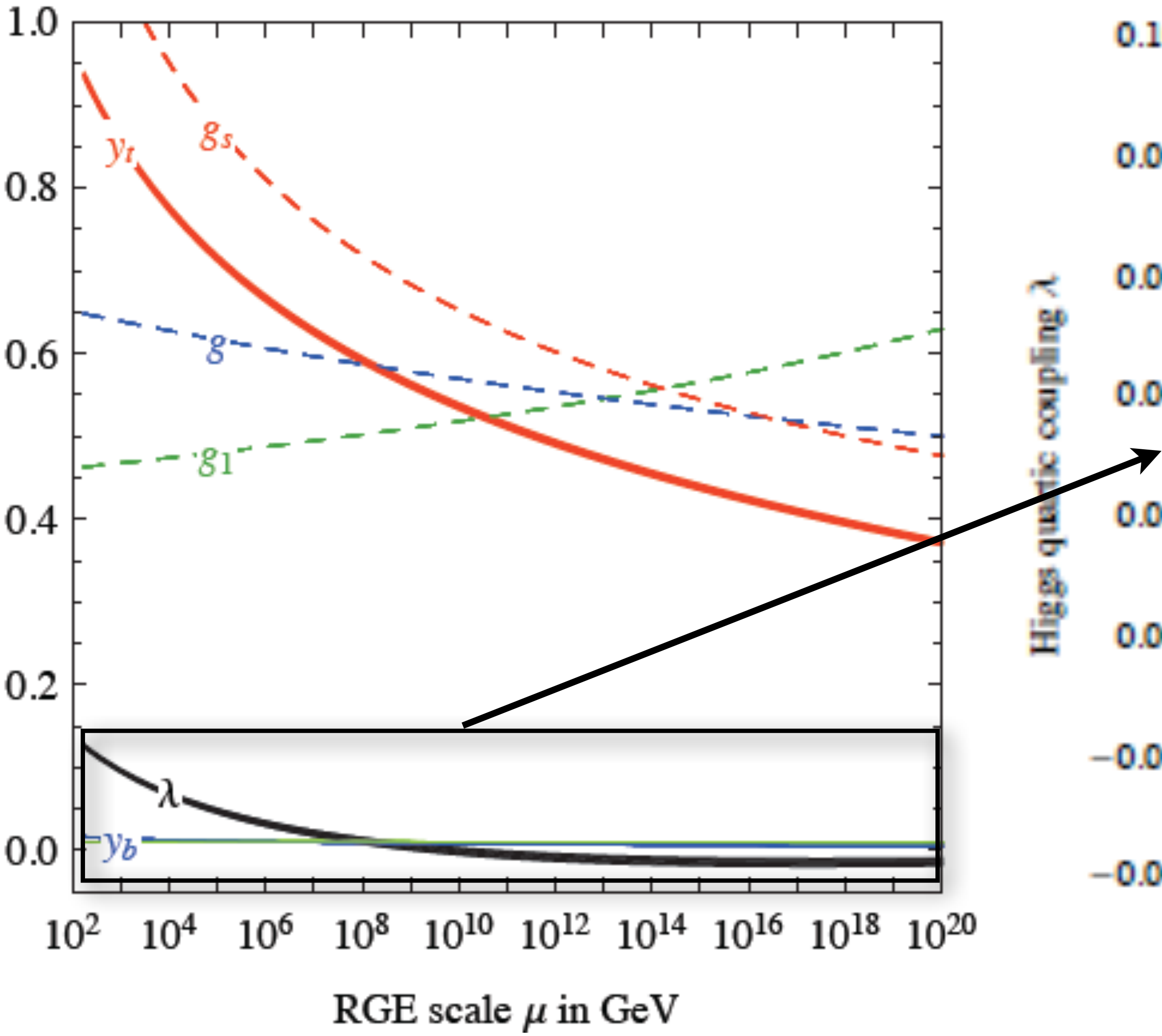
⇒ most (all) questions answered

or, maybe, a clash!

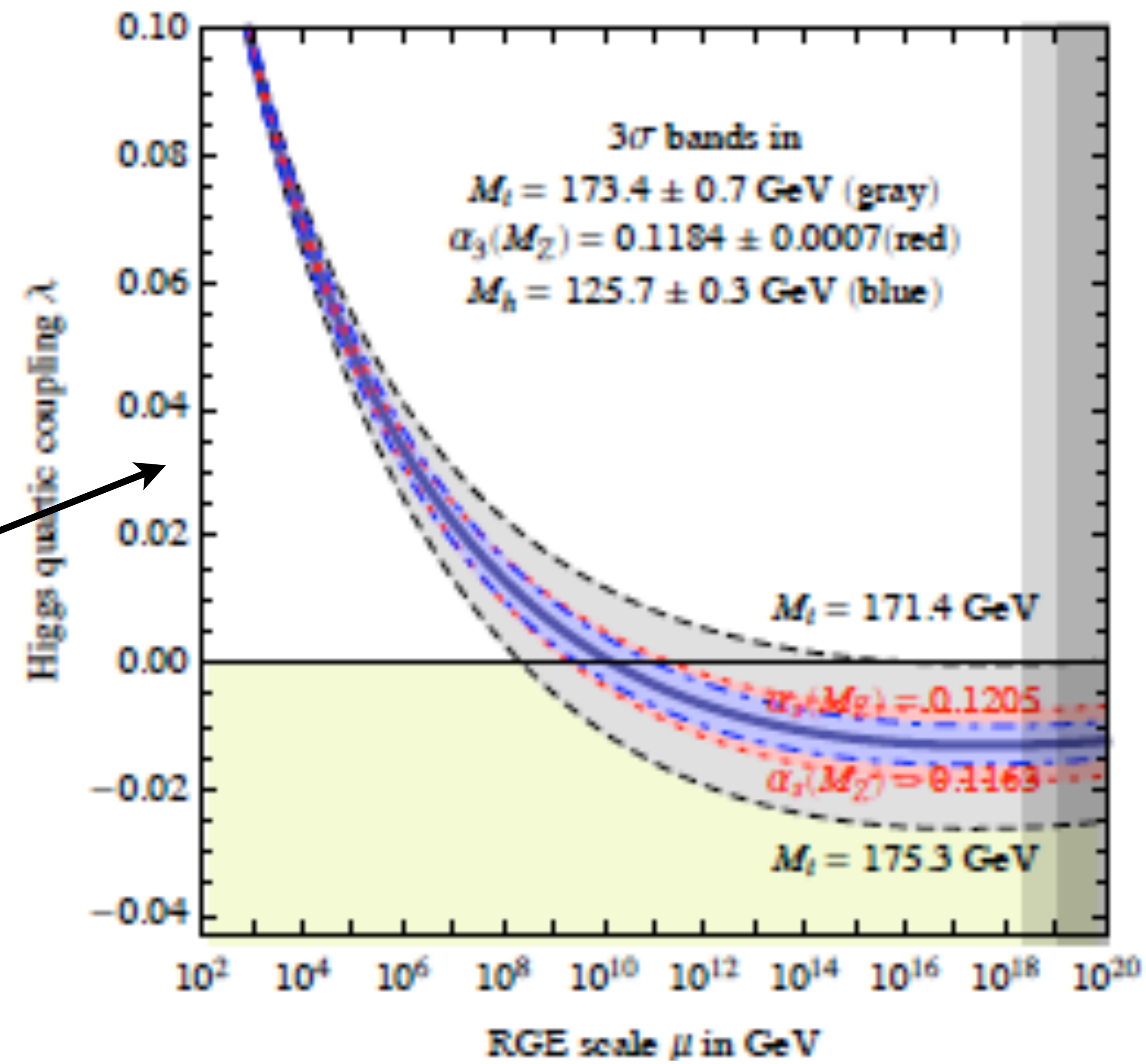


What if one does not care about naturalness and the SM is unchanged up to very high energies?

largest couplings



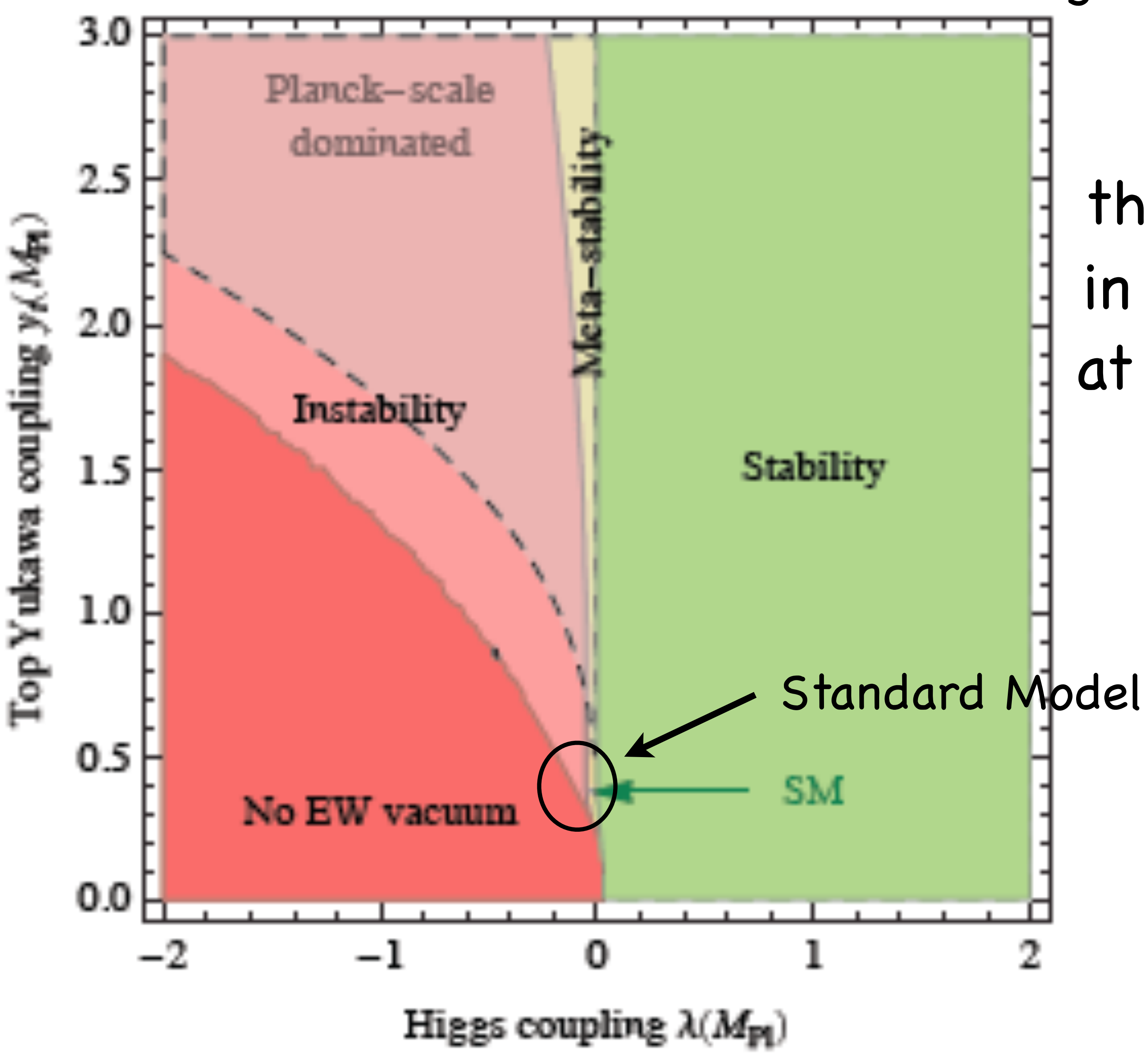
Higgs self-coupling



Degrassi et al 2012
Buttazzo et al 2013

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)

About naturalness

a dominant paradigm in the last thirty years

In the current field theory framework:

naturalness 1:

$m_{Pl} = (\hbar c/G_N)^{1/2} \approx 10^{19}\ GeV \qquad l_{Pl} = \hbar/(m_{Pl} c) \approx 10^{-33}\ cm$

Why there is a large universe ($\Lambda \approx 10^{-3}\ eV << m_{Pl}$)?

Why there are large objects in it ($m_h << m_{Pl}$)?

naturalness 2:

Can we do physics at different scales without knowing the details at shorter distances?

Atomic physics	Nuclear physics	EW physics	? physics	gravity

Apparently not at the moment!

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

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

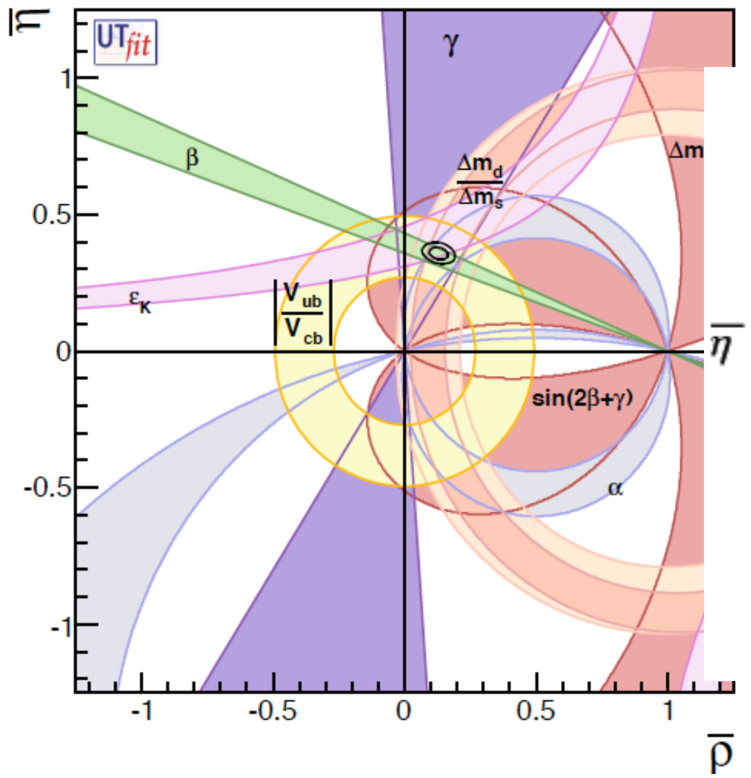
	$\sin\phi = 0$	$\sin\phi = 1$
$\Delta S = 2$	$10^3 \div 10^4$	$2(10^4 \div 10^5)$
$\Delta C = 2$	$(1 \div 5)10^3$	$(0.3 \div 1)10^4$ $[(1 \div 5)10^4]$* ◇
$\Delta B_d = 2$	$(0.5 \div 2)10^3$	$(1 \div 3)10^3$
$\Delta B_s = 2$	$(1 \div 5)10^2$	$(3 \div 8)10^2$ $[(0.5 \div 2)10^3]$*
$\mu \to e\gamma$	$0.5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

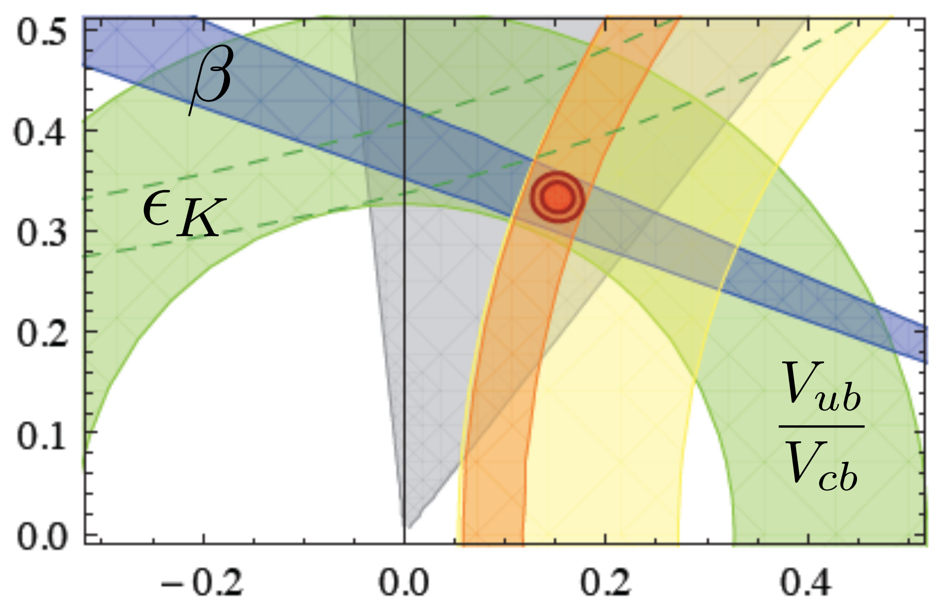
- bounds on $\Delta F = 1$ at $10 \div 100$ TeV
- range depends on Lorentz structure of $\mathcal{O} = \bar{f} f \bar{f} f$
- [ ]* = expected LHCb sensitivity(?)

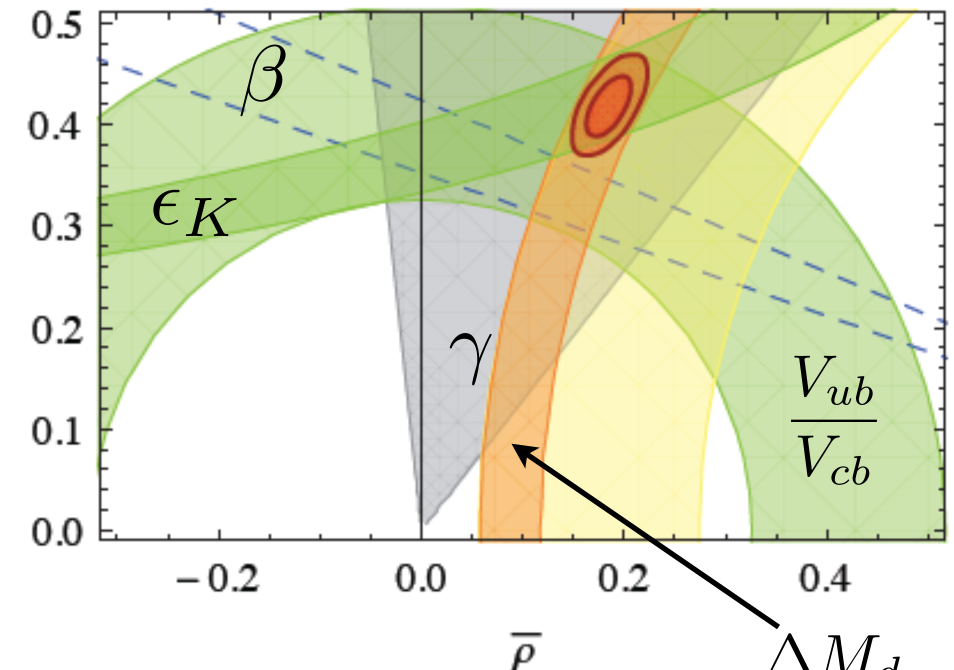
◇ if $(|\frac{p}{q}|_D - 1) \lesssim 10^{-3}$ in the SM defendable (!?)

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

$\Delta F = 2$ key measurements







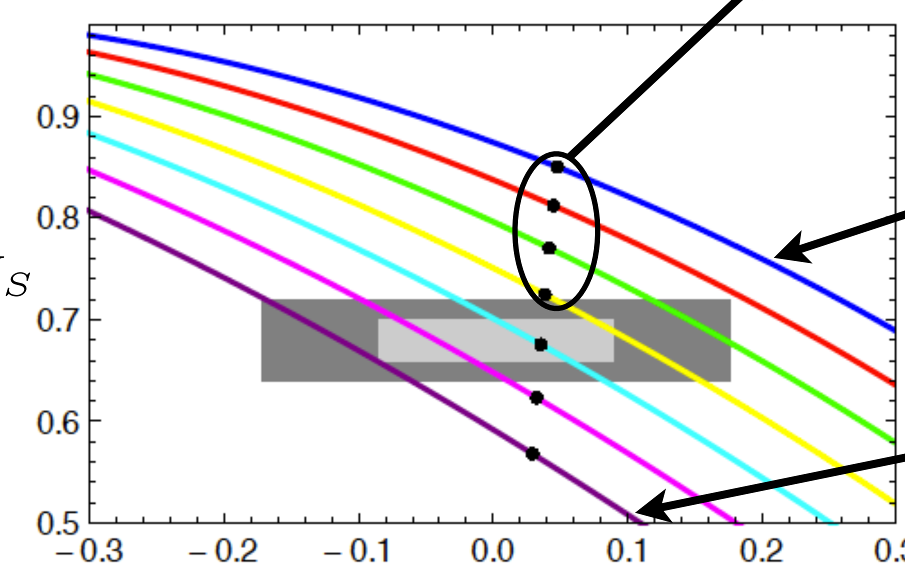
$\frac{\Delta M_d}{\Delta M_s}$

$\Rightarrow \gamma \approx 70^0$

$U(2)^3$

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



$|V_{ub}| = 0.0046$

$|V_{ub}| = 0.0028$

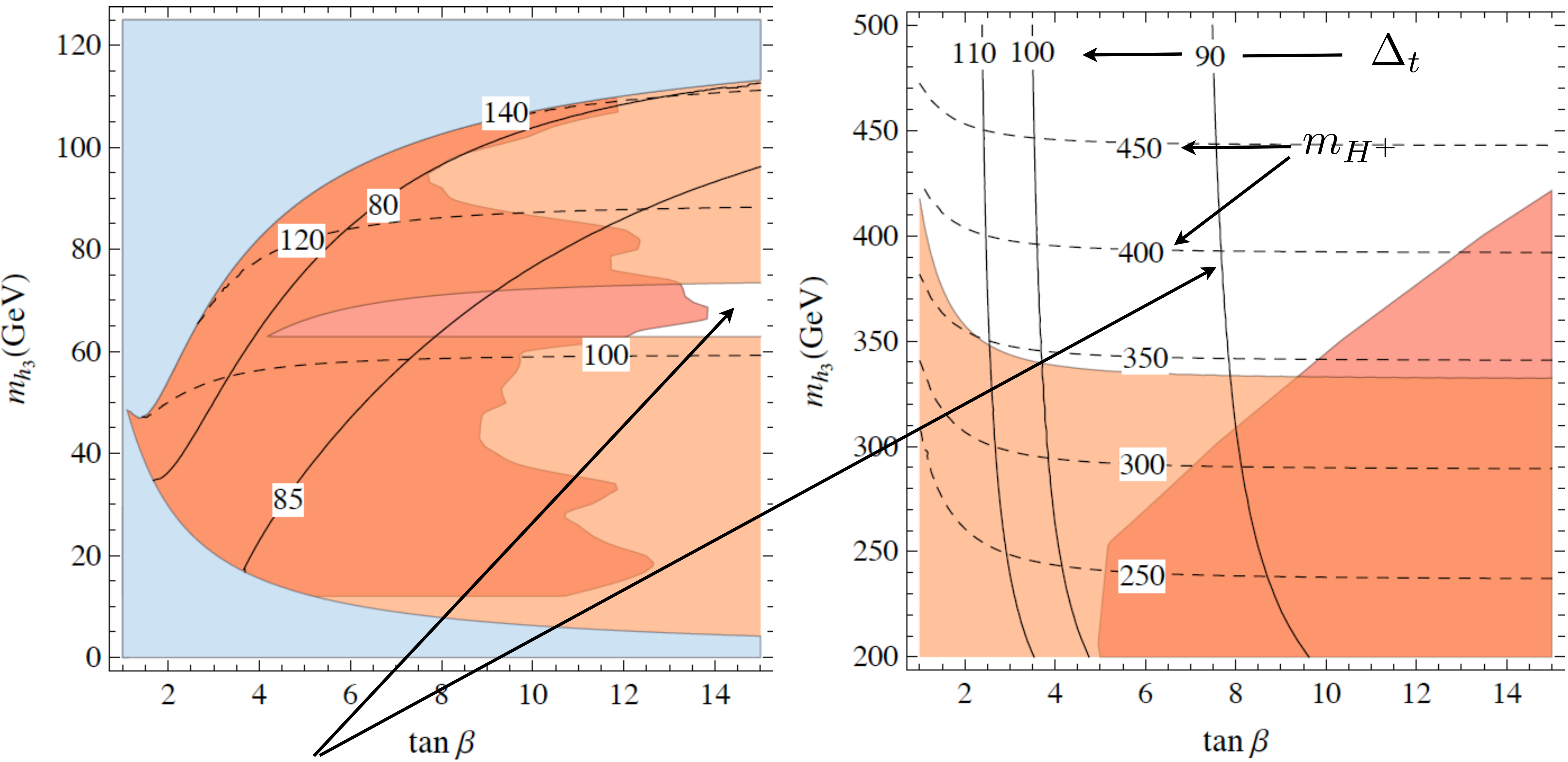
Buras, Girrbach

The theory community after the first LHC phase

(Savas Dimopoulos, GGI, July 2013)

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

$h_3 < h_{LHC}$ $\qquad\qquad$ $h_{LHC} < h_3$



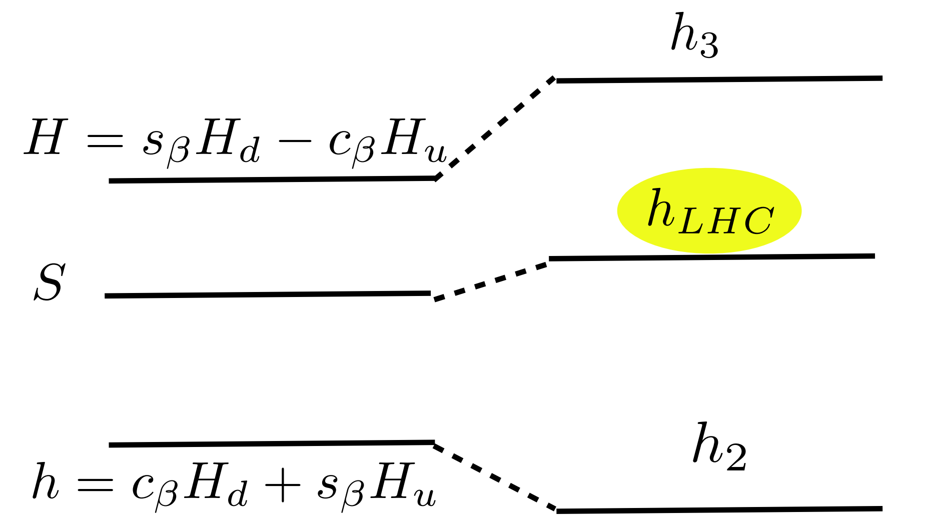
region still allowed
only for largish Δ_t

orange = excluded by h_{LHC} - measurements

red = excluded by direct searches

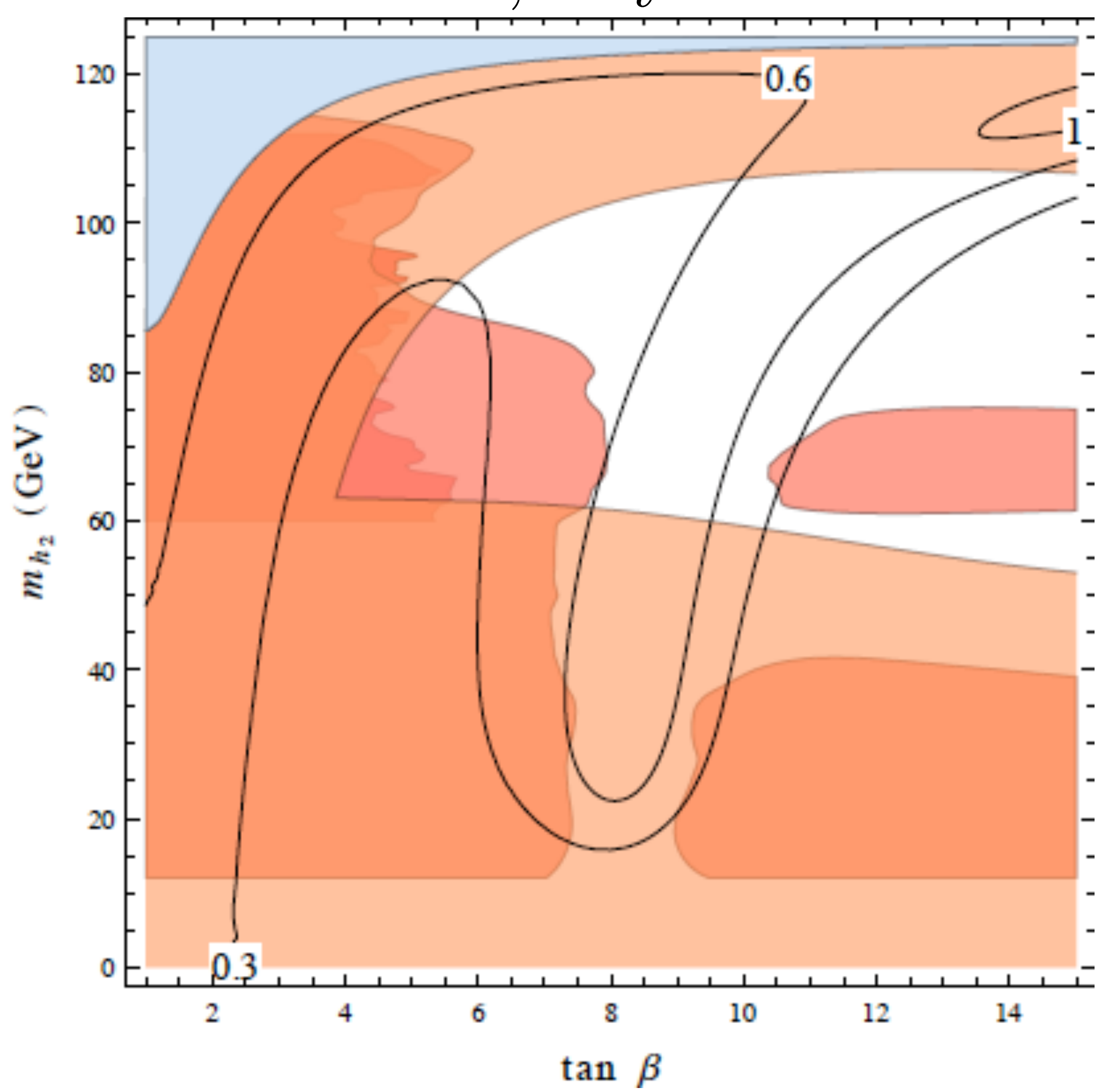
LEP ($h_3 < h_{LHC}$) $\qquad$ LHC ($h_{LHC} < h_3$)

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

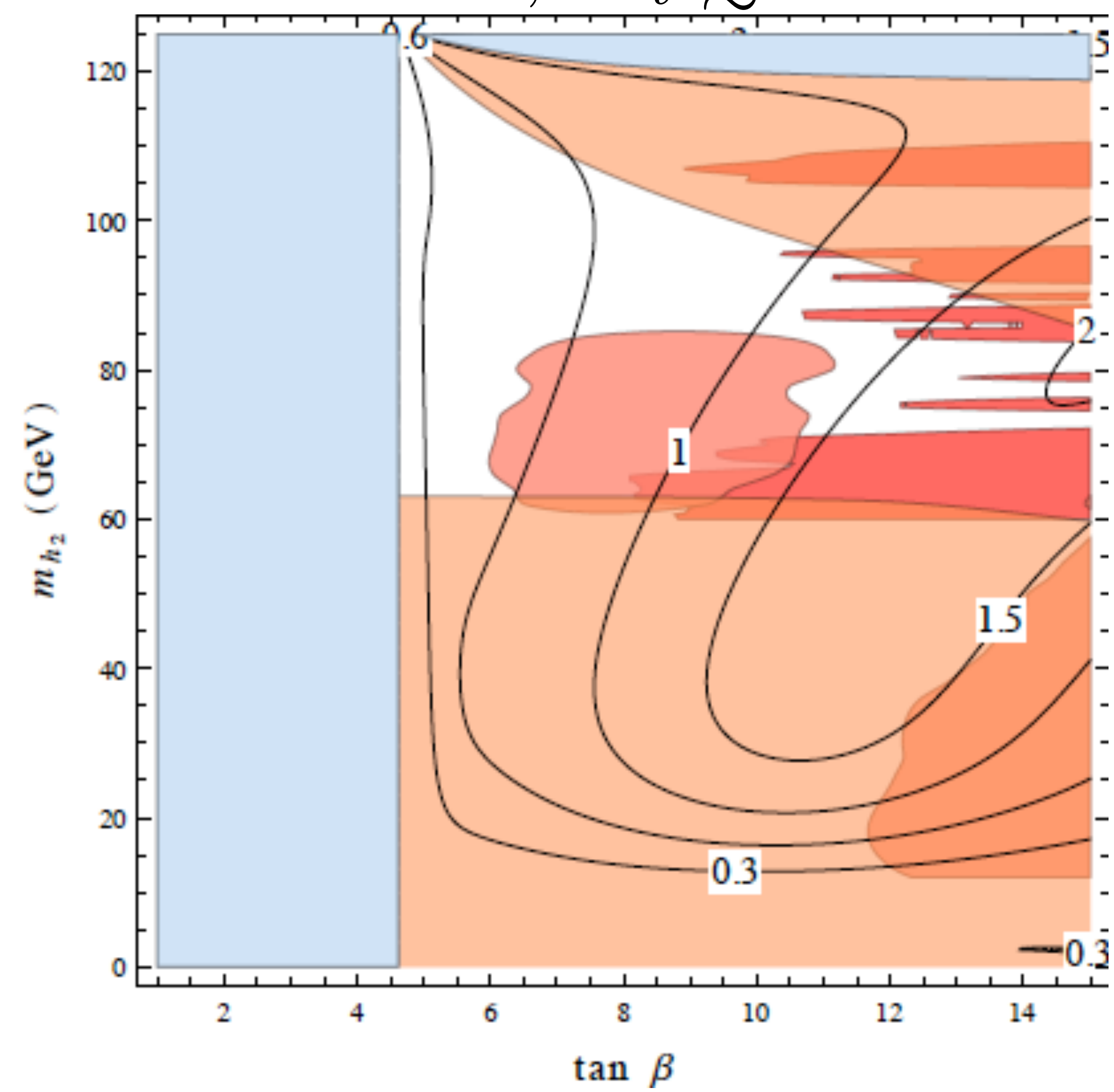


isolines of $\mu(h_2 \to \gamma\gamma)$ normalized to SM

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



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



orange = excluded by h_{LHC} - measurements

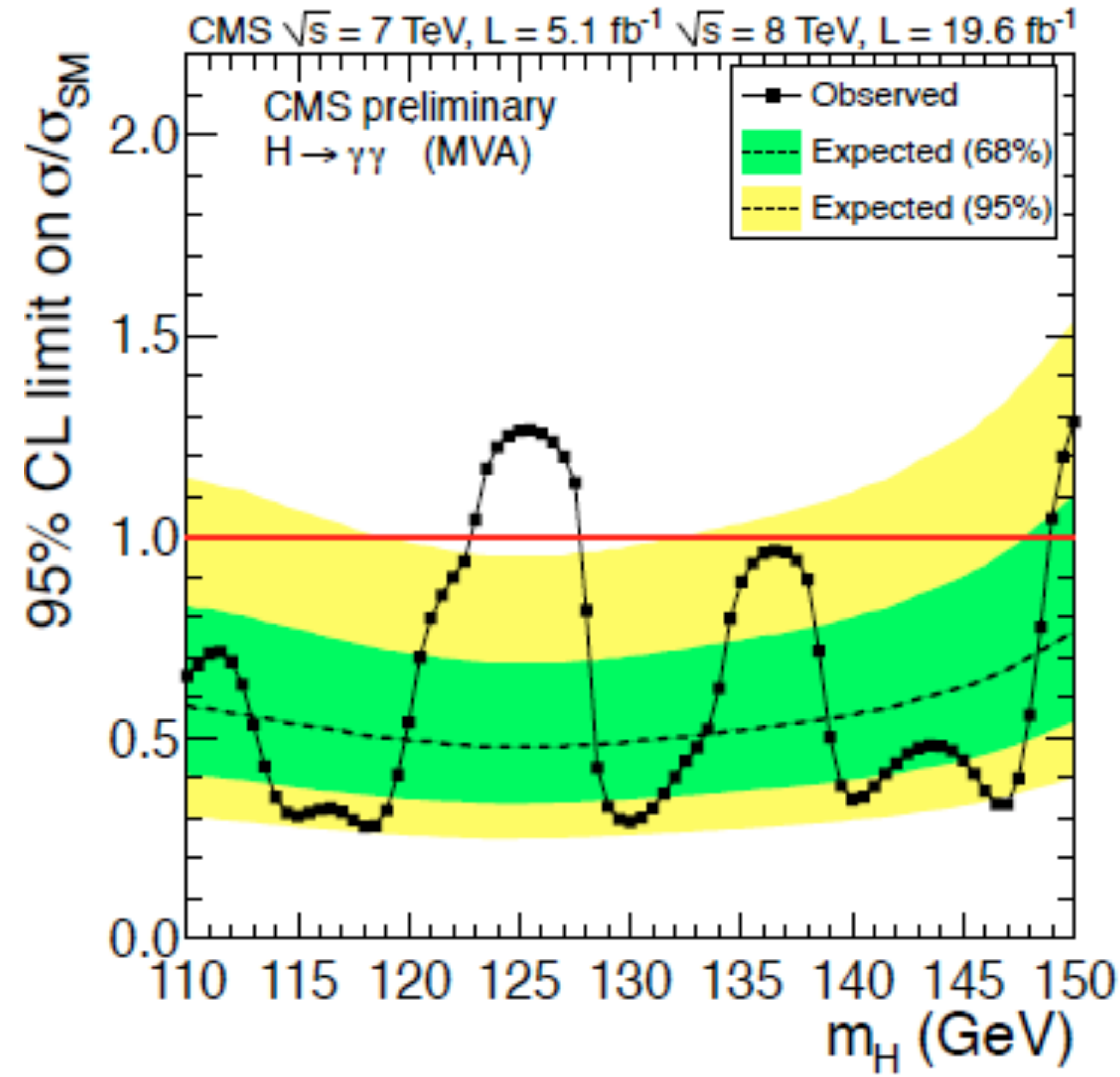
red = excluded by LEP in $h_2 \to b\bar{b}$

blue = unphysical

magenta = excluded by LEP in $h_2 \to$ hadrons

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

(Pokorski et al)



The $\Delta F = 2$ case

$U(3)^3$

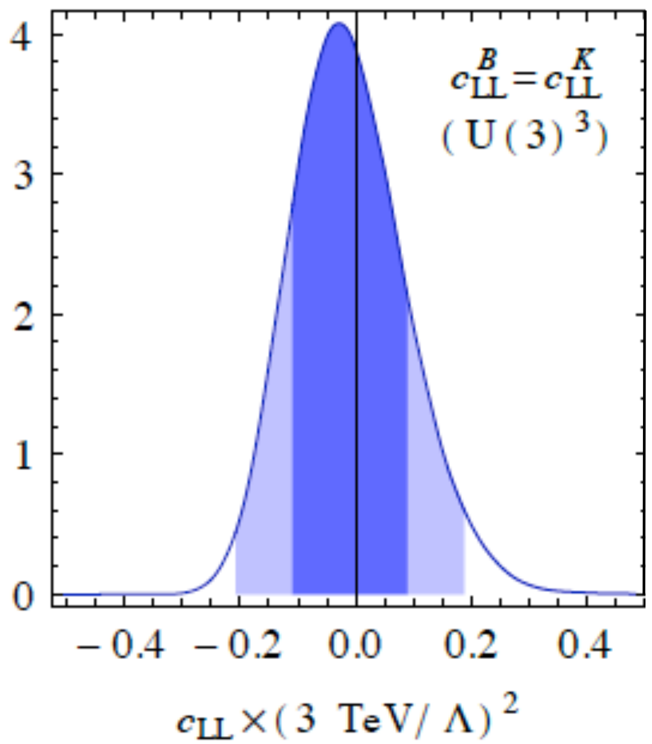
$U(2)^3$

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

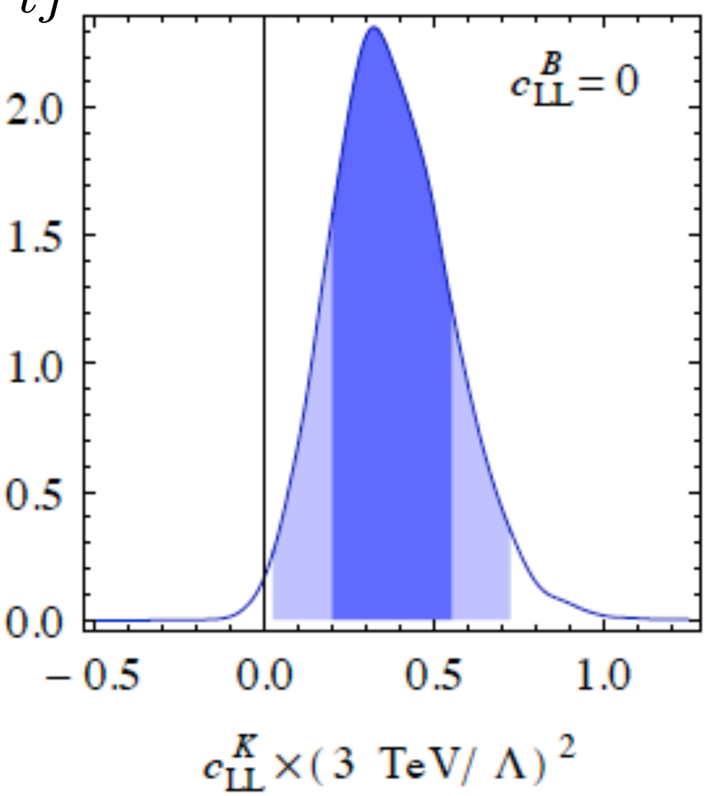
$$\xi_{ij} = V_{ti}V_{tj}^*$$

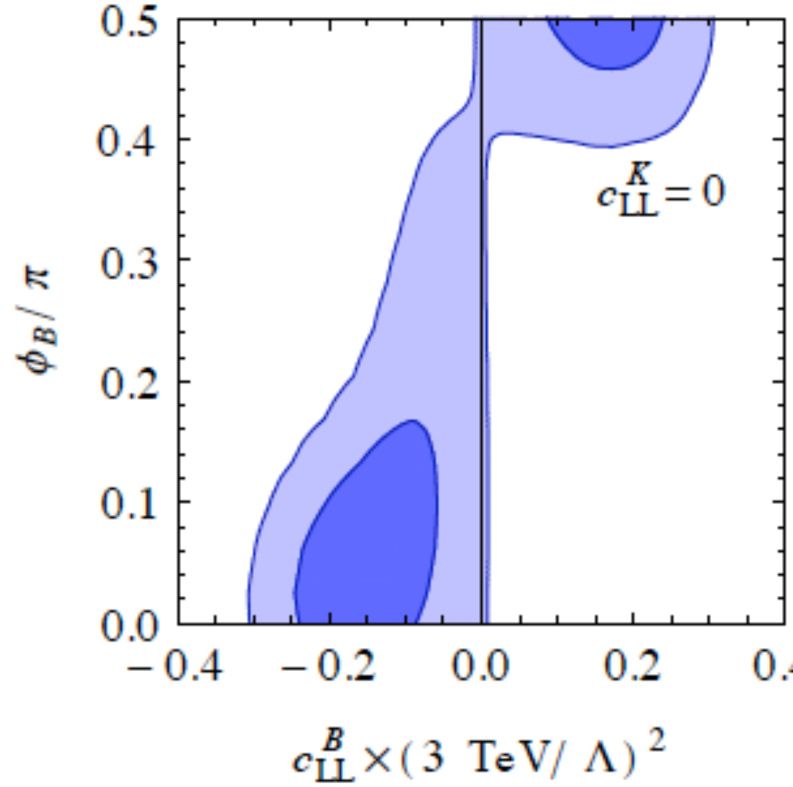
$$\frac{c_{LL}^K}{\Lambda^2}\xi_{ds}^2 \frac{1}{2}(\bar{d}_{L}\gamma_\mu s_{L})^2$$

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



(cannot fit the "discrepancy")





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

Flavour tests
versus direct searches
(cum grano salis)

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

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

$\Delta F = 1$ Summary

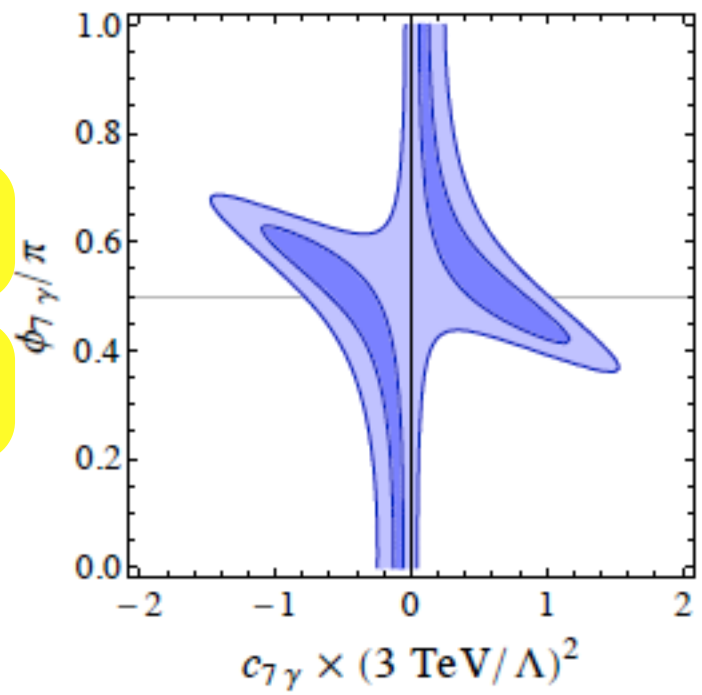
Chirality breaking (cromo-)magnetic operators

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

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

$U(3)^3$

$U(2)^3$



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

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

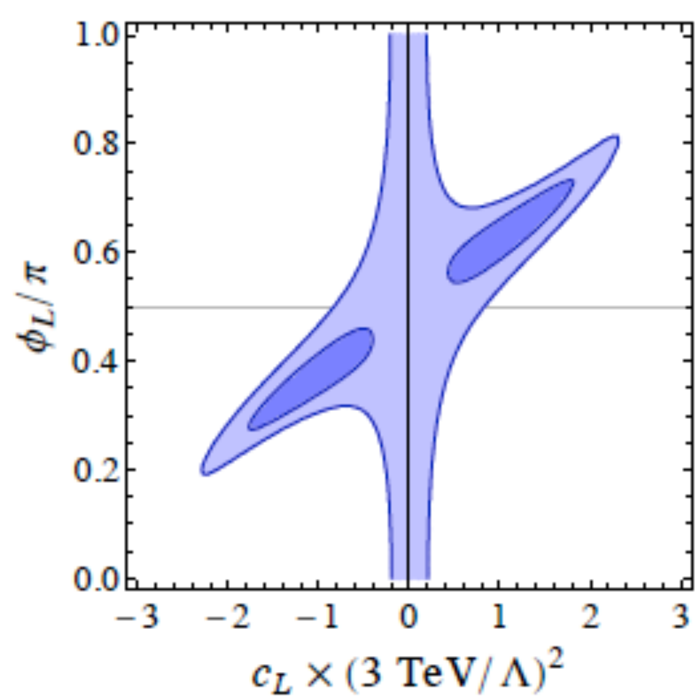
$B \to K(\pi)\mu\mu$ } correlated

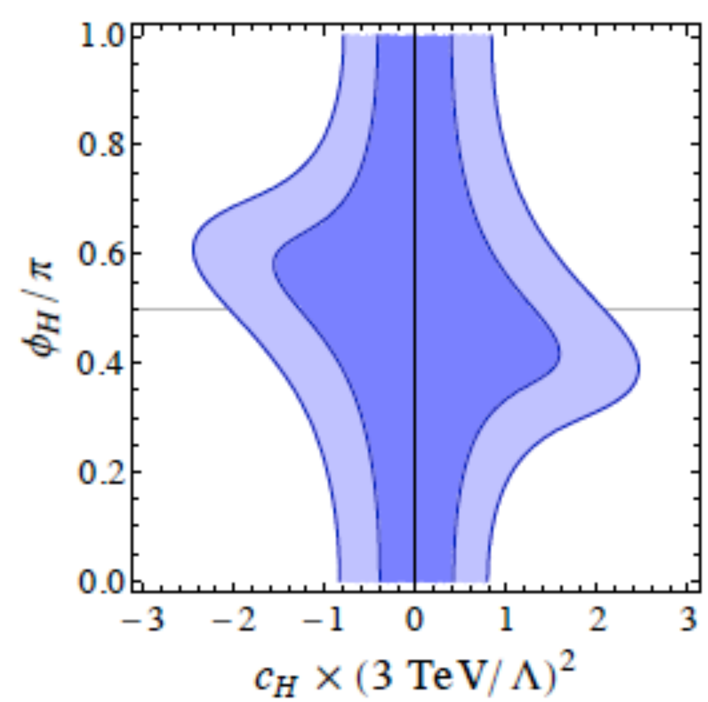
$B_s \to \mu\mu$

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

$U(2)^3$

no phase in $U(3)^3$





NMSSM $\Delta f = \lambda H_u H_d$

Fayet 1975

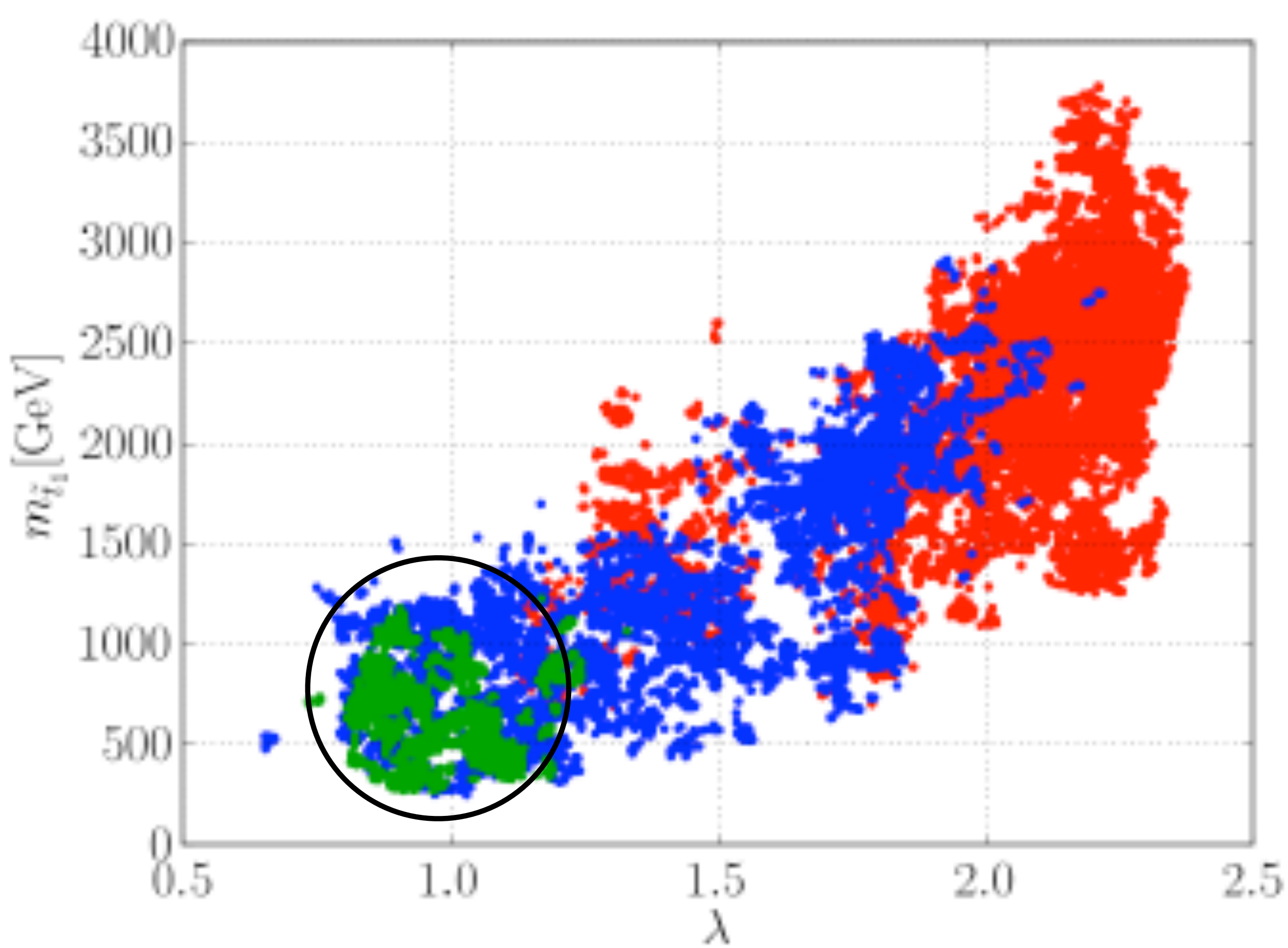
Two independent reasons to consider it:

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