COLLÈGE DE FRANCE
1530

CHAIRE DE PARTICULES ELÉMENTAIRES, GRAVITATION ET COSMOLOGIE
Année académique 2012-2013

M. Gabriele Veneziano, Professeur

Colloque de clôture :
Un boson nommé Higgs

Vendredi 24 mai 2013 à 9h00

# Implications et perspectives theoriques

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# Particle Physics in one page

$\mathcal{L}_{ST}$

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\not{D}\psi$$ The gauge sector 1

$$+|D_\mu h|^2 - V(h)$$ The EWSB sector 2

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$ The flavour sector 3

$$+N_i M_{ij} N_j$$ The ν-mass sector 4
(if Majorana)

+

Dark Matter ✓

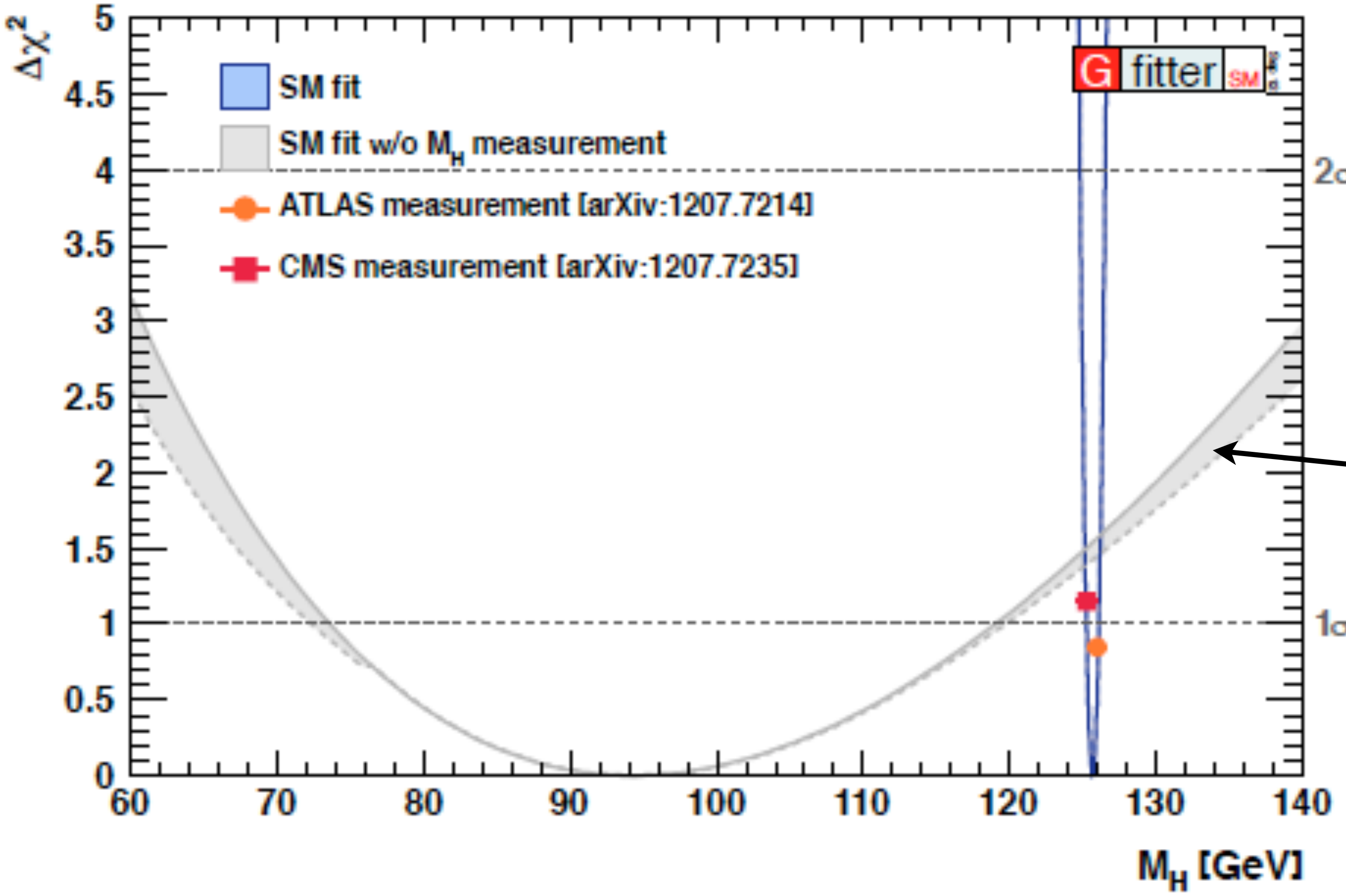
Baryon Asymmetry ✓

Dark Energy

(not included in
current knowledge
of particle physics)

# The great empirical evidence for (and from) the gauge sector

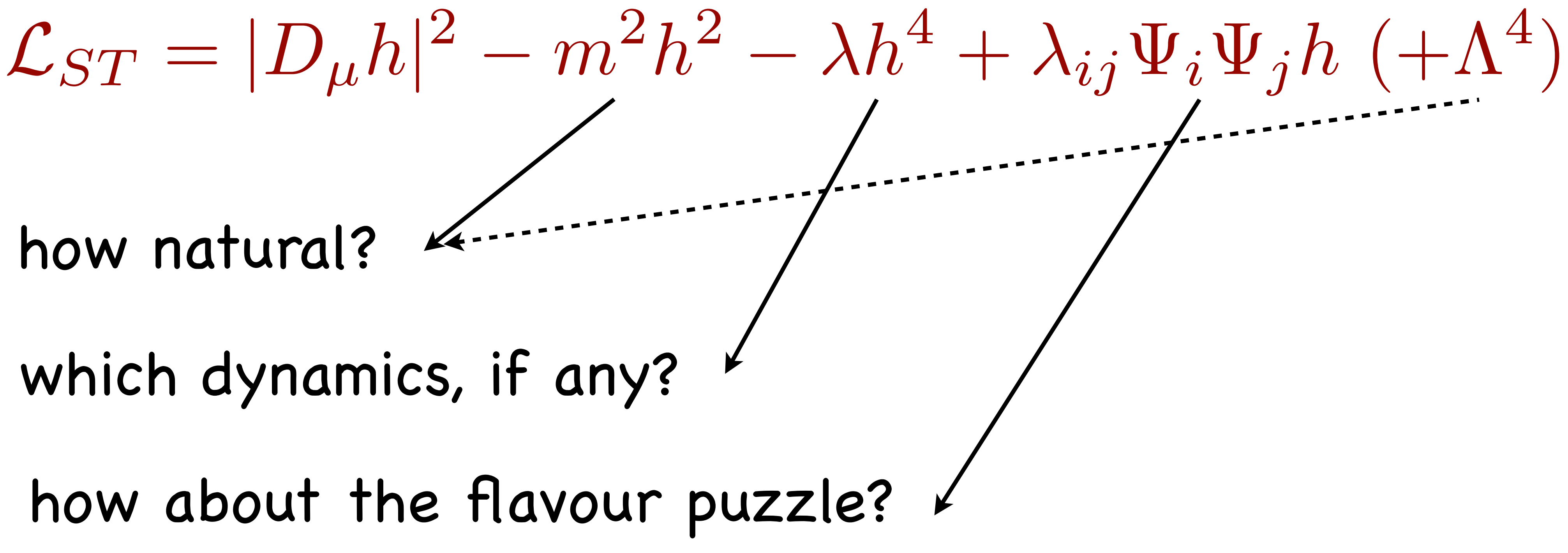
(for extension, precision, diversity)



the $\chi^2$ distribution of $m_h$ w/o the $m_h$ measurements

(with a similar story for the top discovery in 1994)
(and a partially similar story for the W-Z in 1884)

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



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

how natural?

which dynamics, if any?

how about the flavour puzzle?

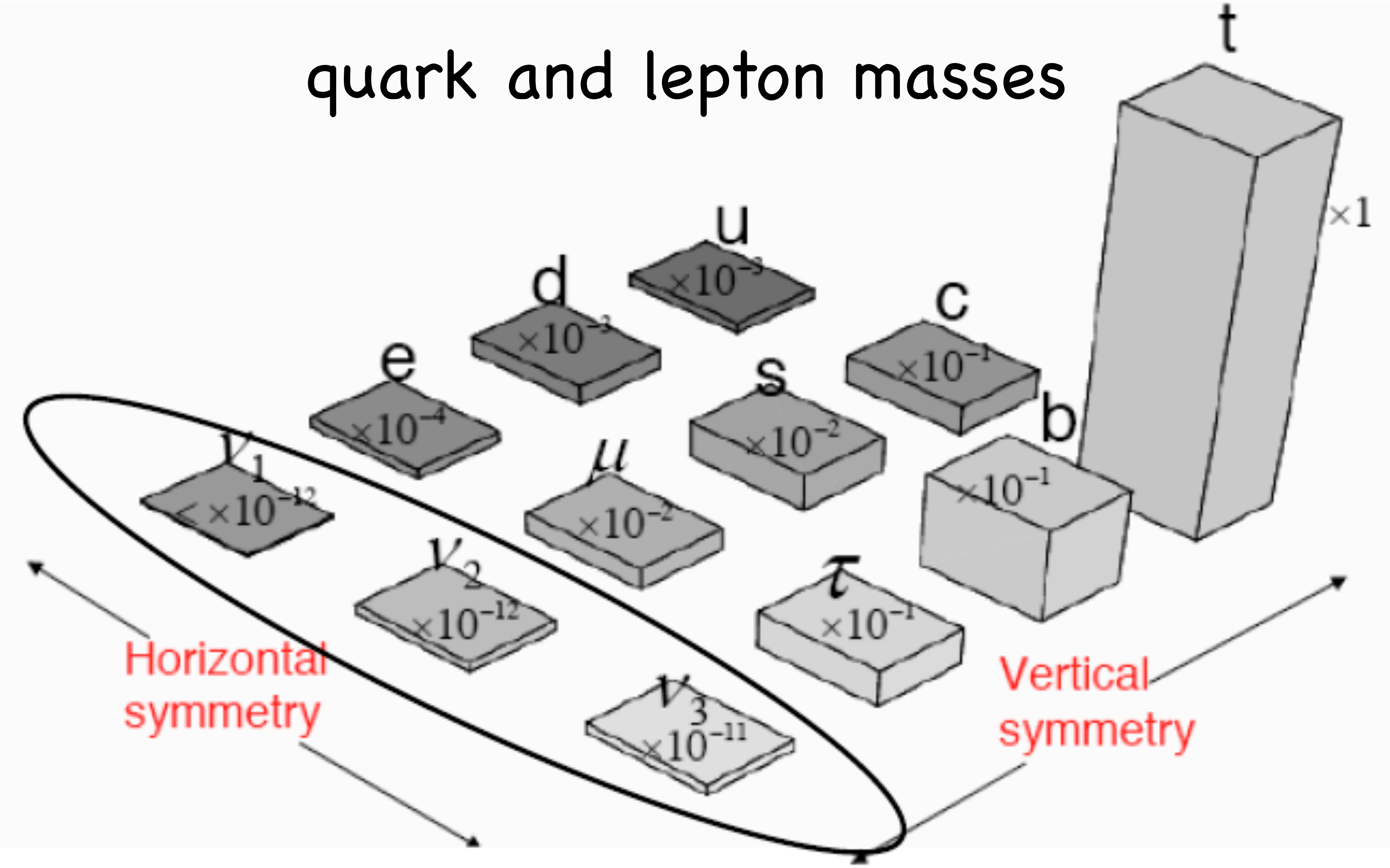
(Note: no physical inconsistency!)

**A paradoxical answer: yes to both alternatives**

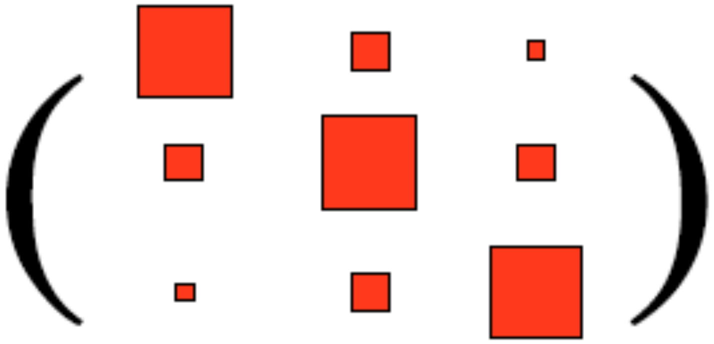
# The flavour puzzle $\lambda_{ij}\Psi_i\Psi_j h$

(not touched in this lecture)

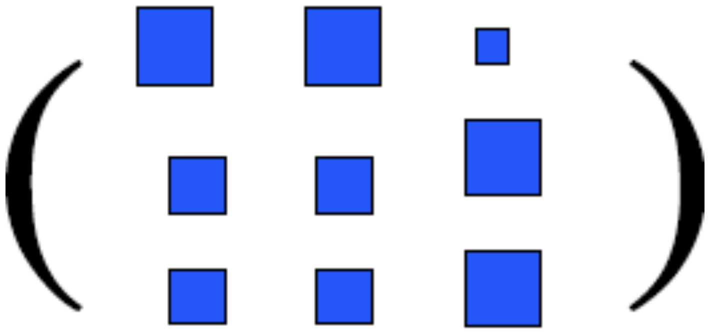
quark and lepton masses



quark mixings



lepton mixings



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

What determines this structure?

Not easy without observed deviations from the SM

# About naturalness

a dominant paradigm in the last thirty years

**naturalness 1:**

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

In the current field theory framework:

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?

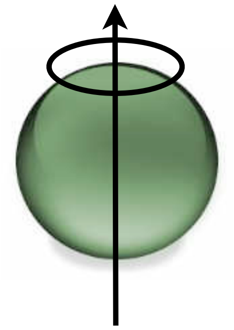
Atomic physics    Nuclear physics    EW physics    ? physics    gravity

Apparently not at the moment!

# naturalness 3:

Among the many examples that beautifully work so far

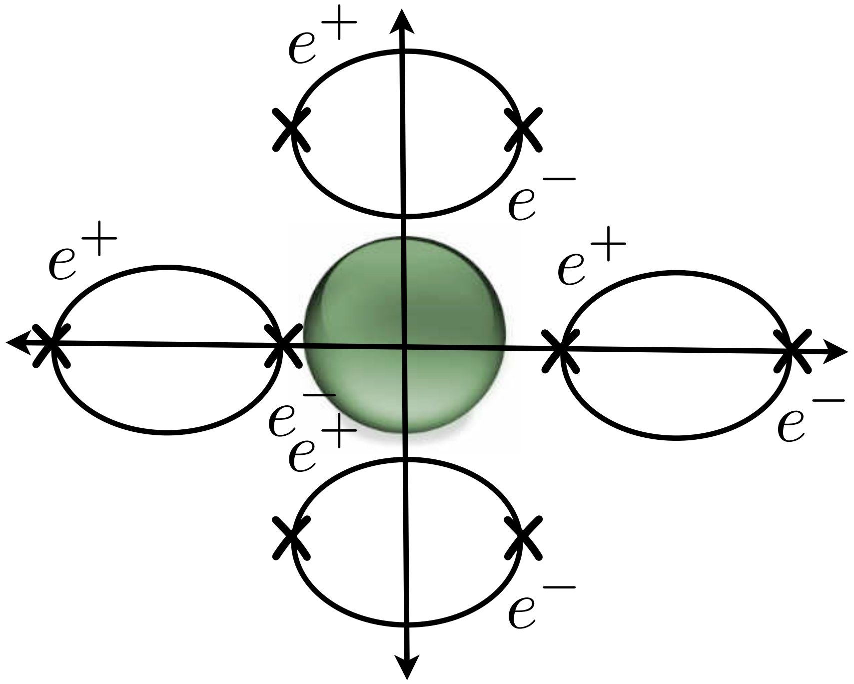
the electron self energy:



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



Weisskopf 1939

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

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

# Back to the Higgs boson

What one needs to know:

⇒ Its quantum numbers: $J^{PC} = 0^{++}$, gauge q.n.s

⇒ The strength of its interactions
with all other particles and with itself

⇒ Is it "natural"?

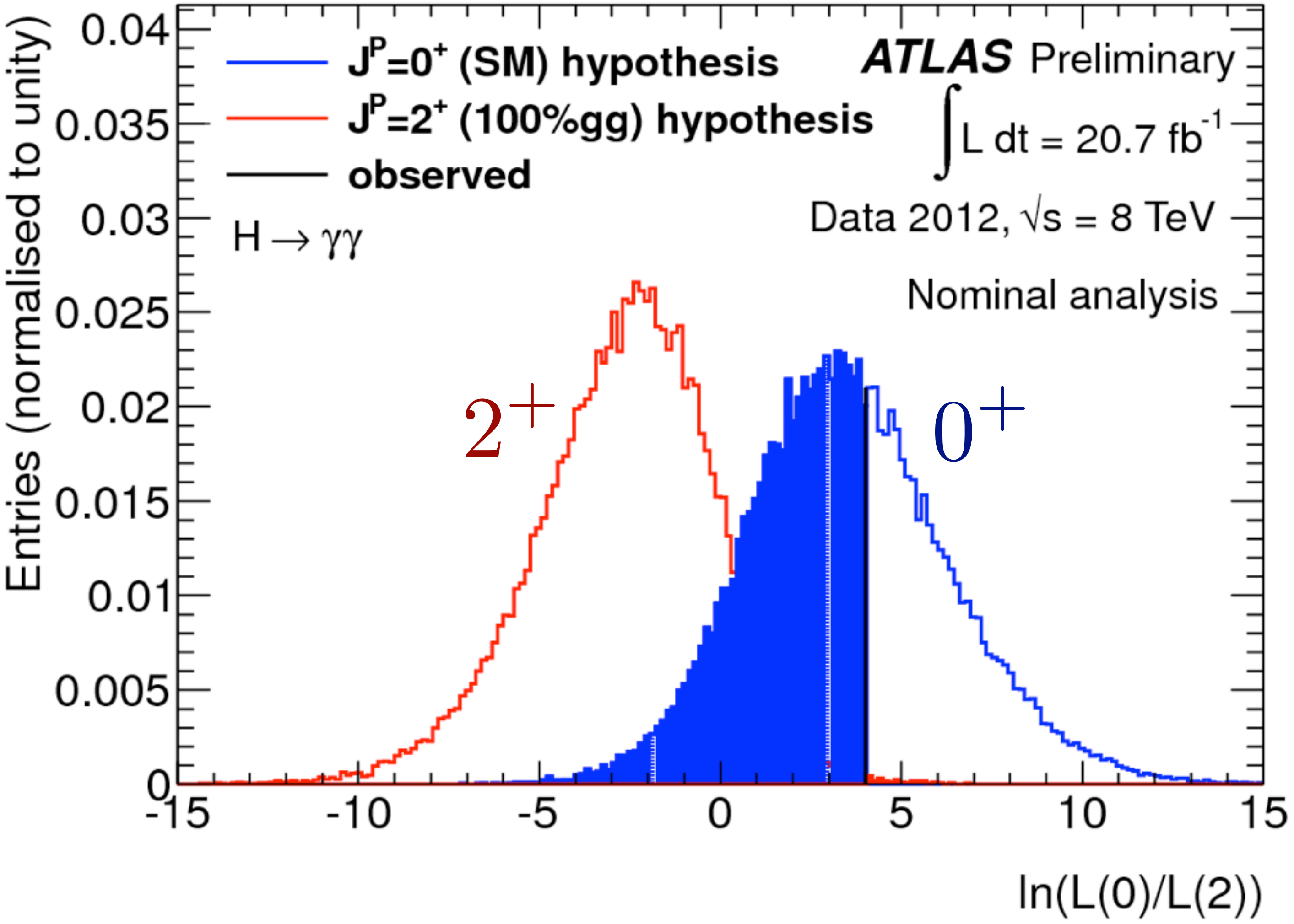
⇒ Is it "elementary" or "composite"?

⇒ Is it alone or accompanied?

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

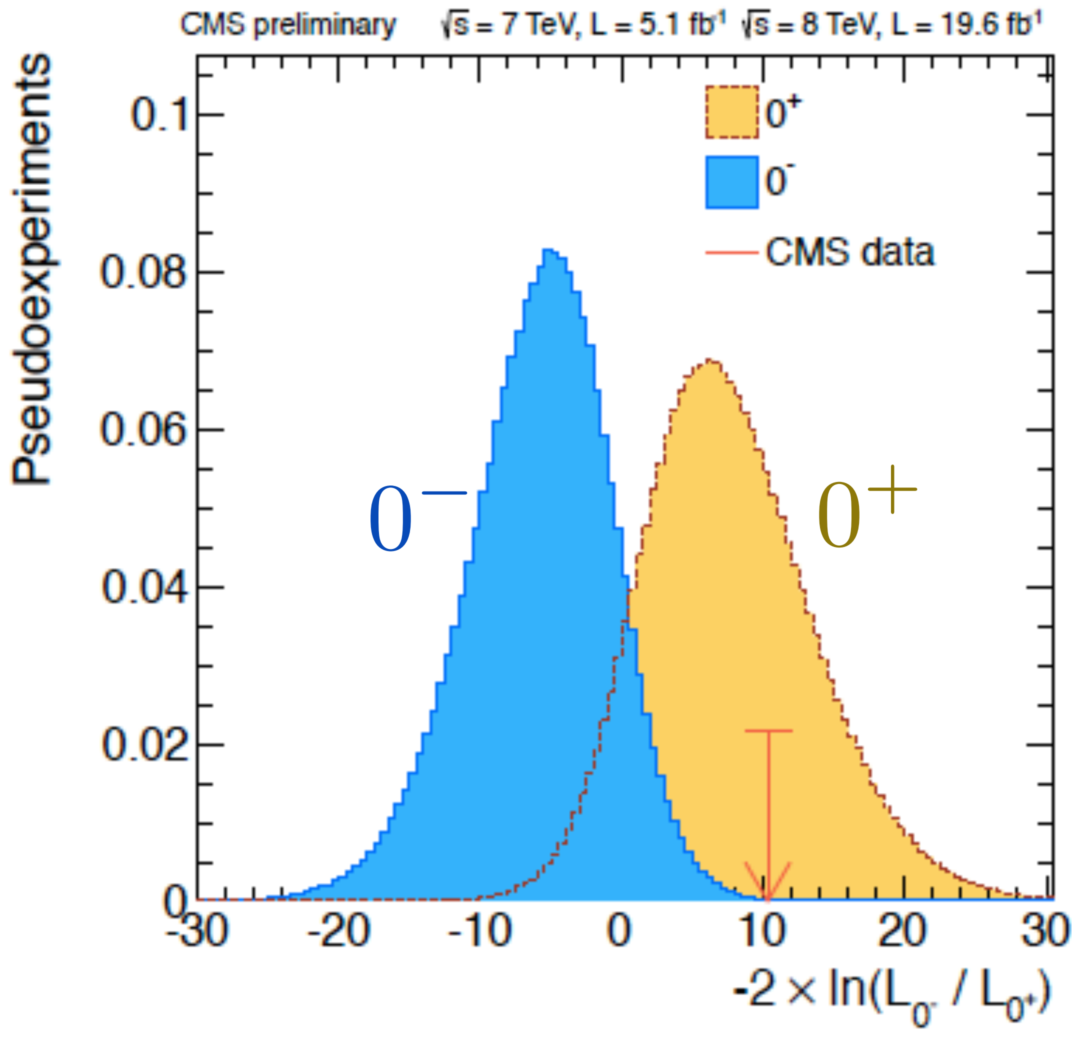
Parity and angular momentum discrimination by angular distribution in decays (pairwise hypothesis tests)

$h \to \gamma\gamma$



the angular momentum looks right

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

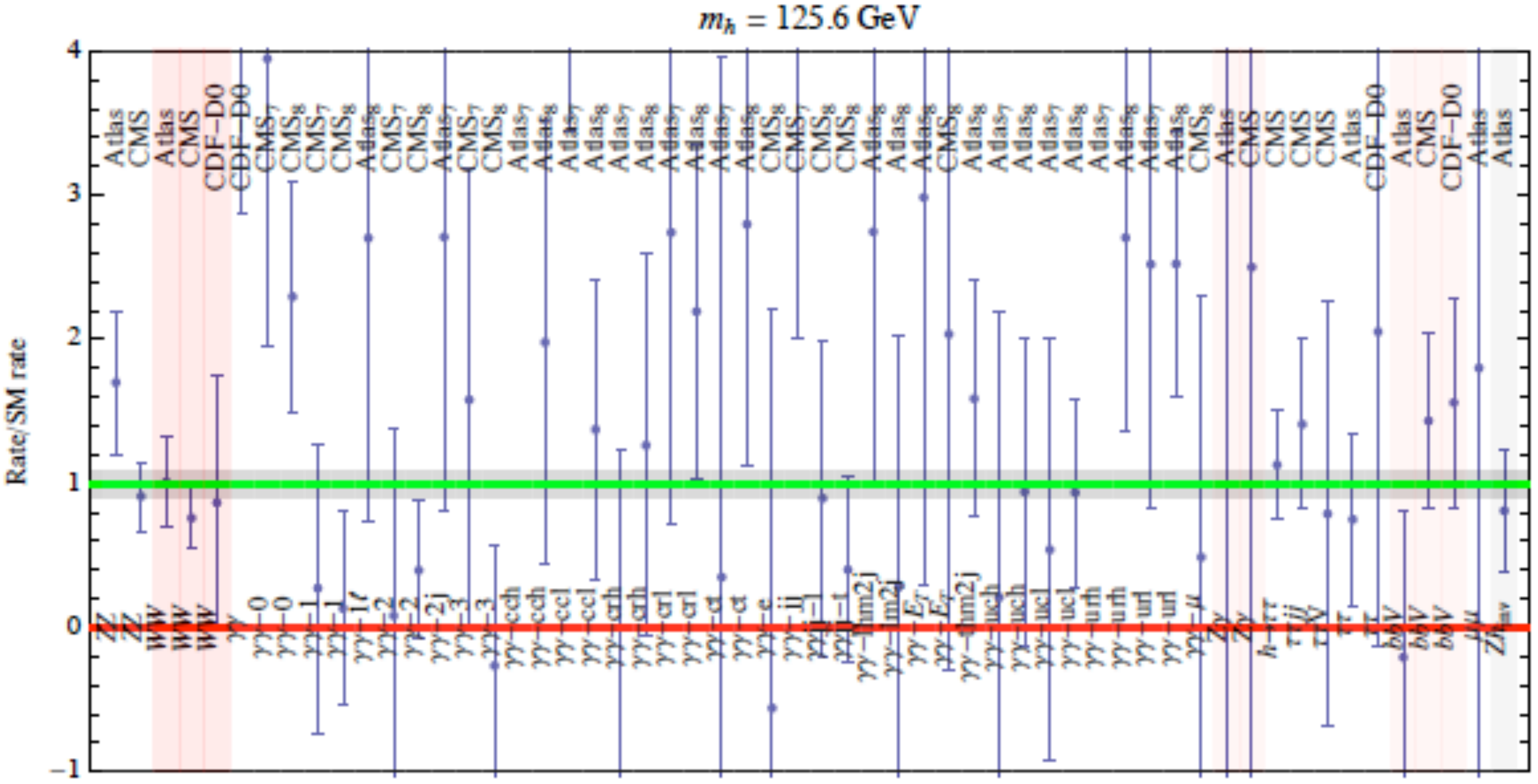


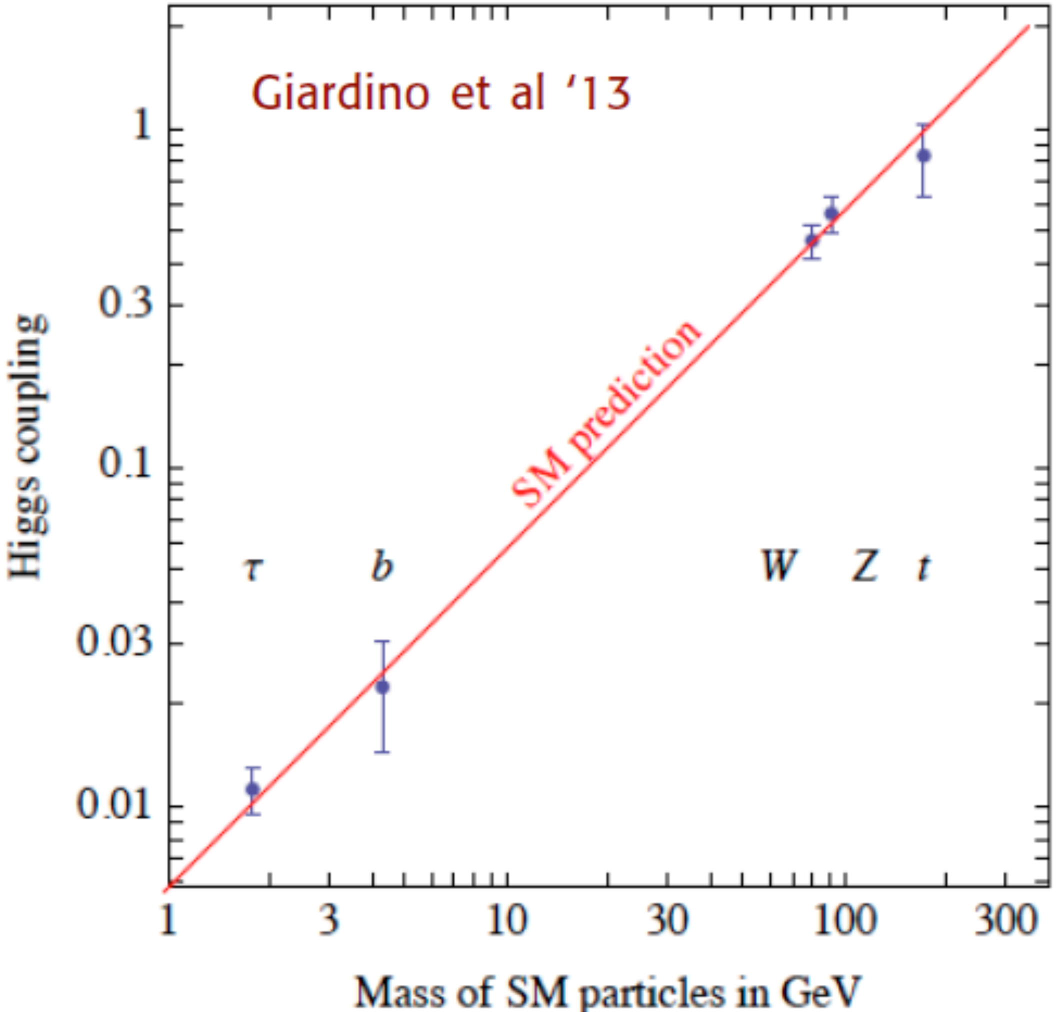
the parity looks right

# The couplings to other particles

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

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

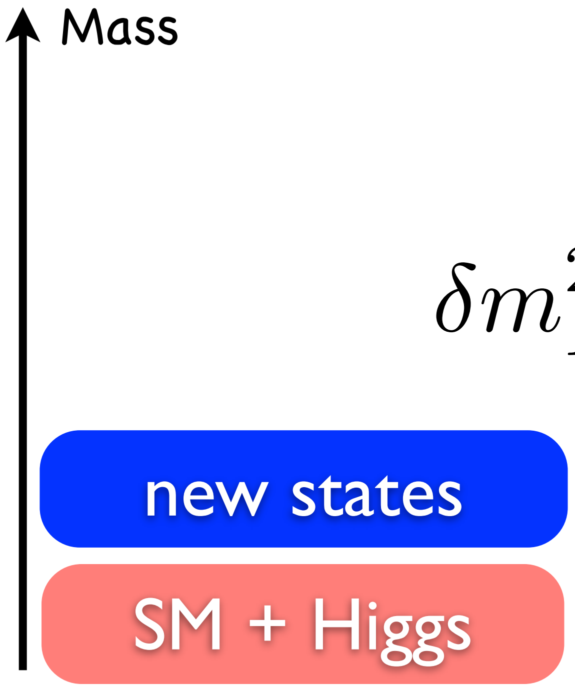




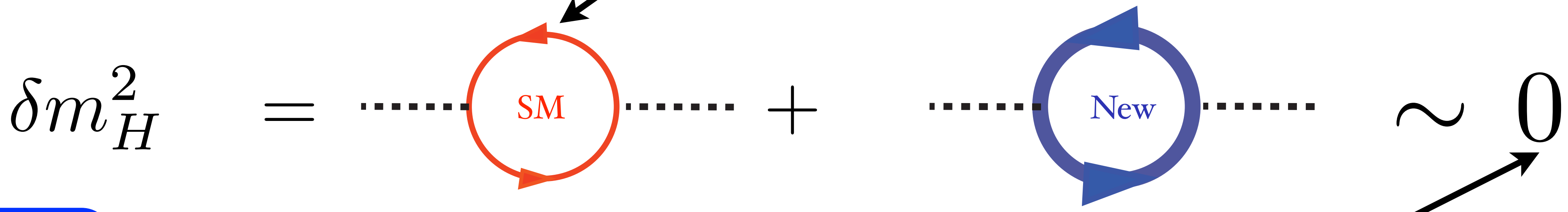
The coupling-versus-mass linear relation is
an absolute prediction of the ST (not exhaustive: $gg, \gamma\gamma$ )

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

# A “natural”, not Fine Tuned Higgs boson



mostly the top

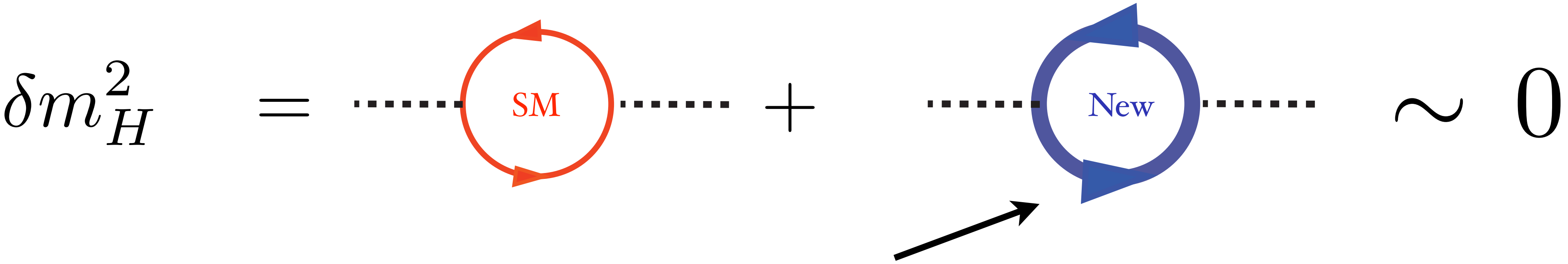


by an (approximate) symmetry

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

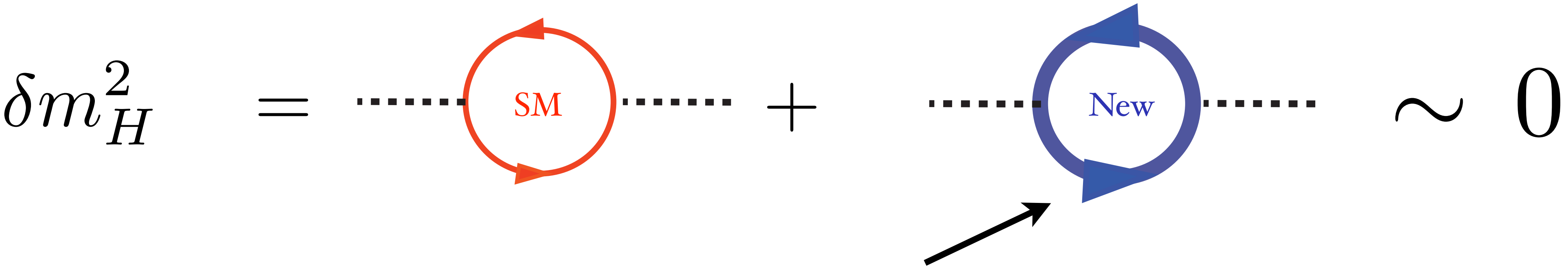
If so, explain why the great empirical success of the SM does not depend on unknown short distance physics

# Supersymmetry



s-particles

# The Higgs boson as a pseudoGolsdtone



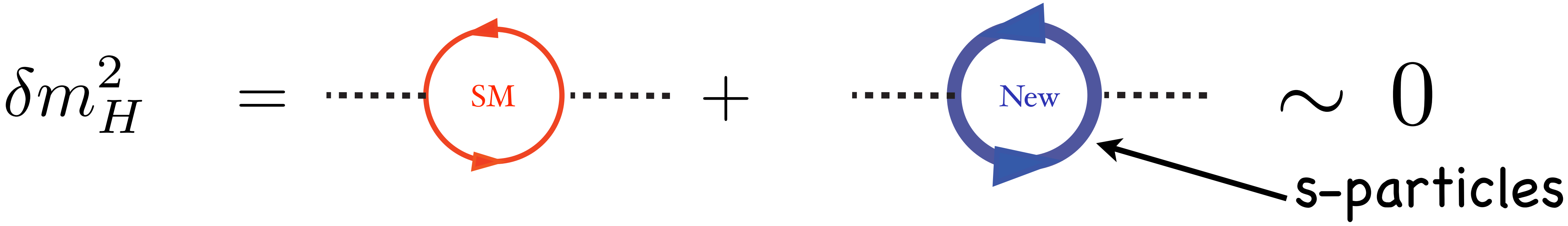
Heavy "composite" fermions

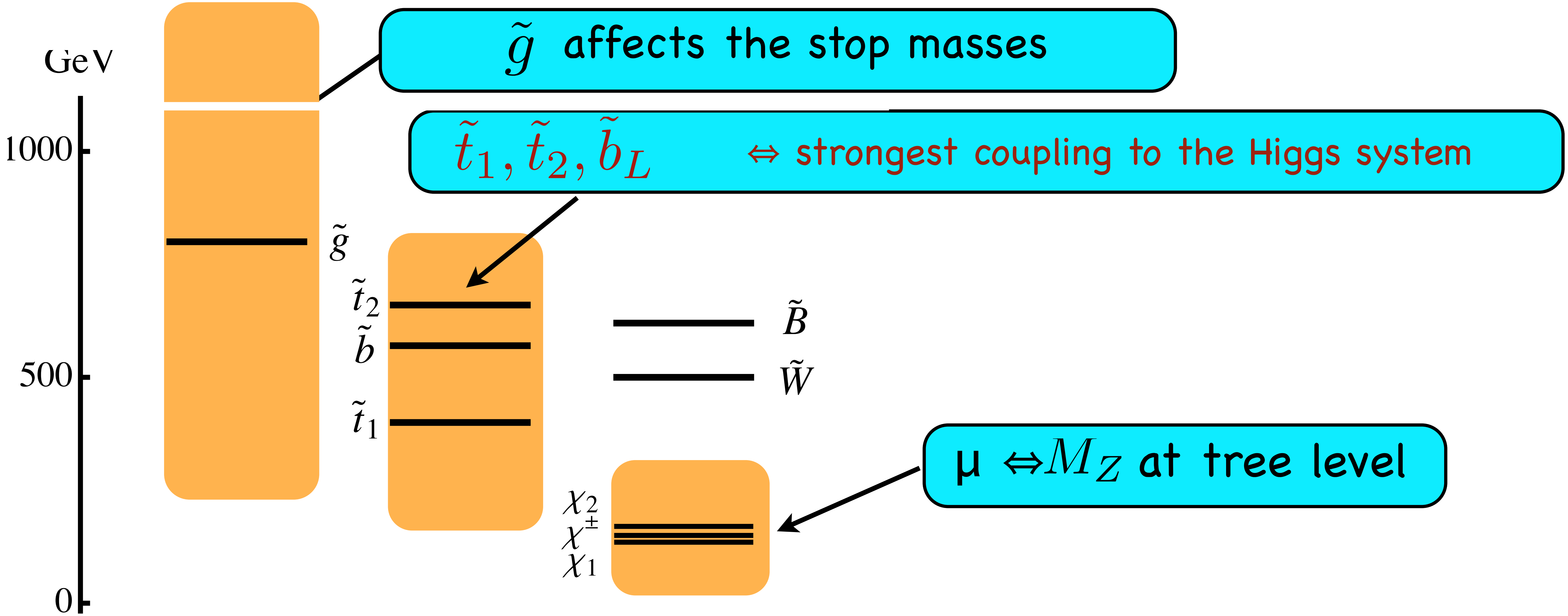
Question: Nothing seen so far. Shouldn't we worry?

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

# The “crucial” configuration of supersymmetry

(introduced well before the LHC)



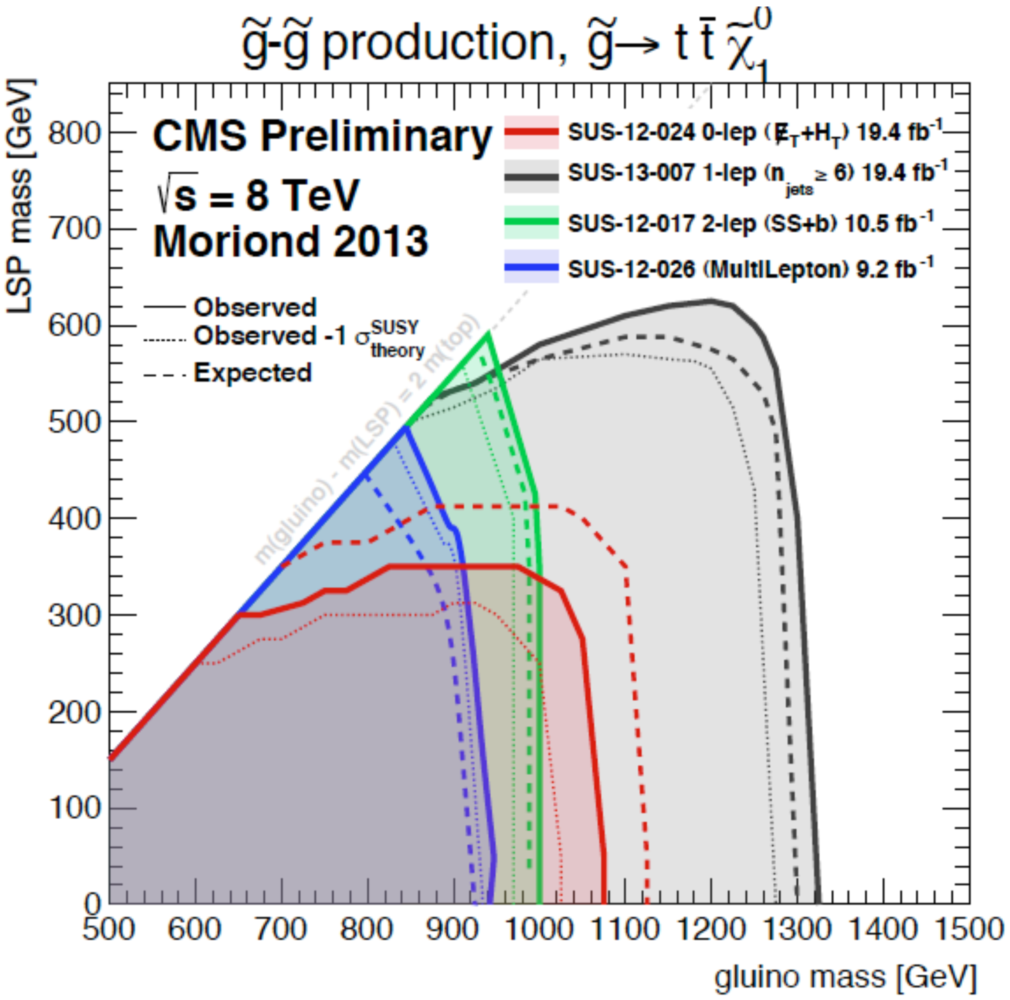


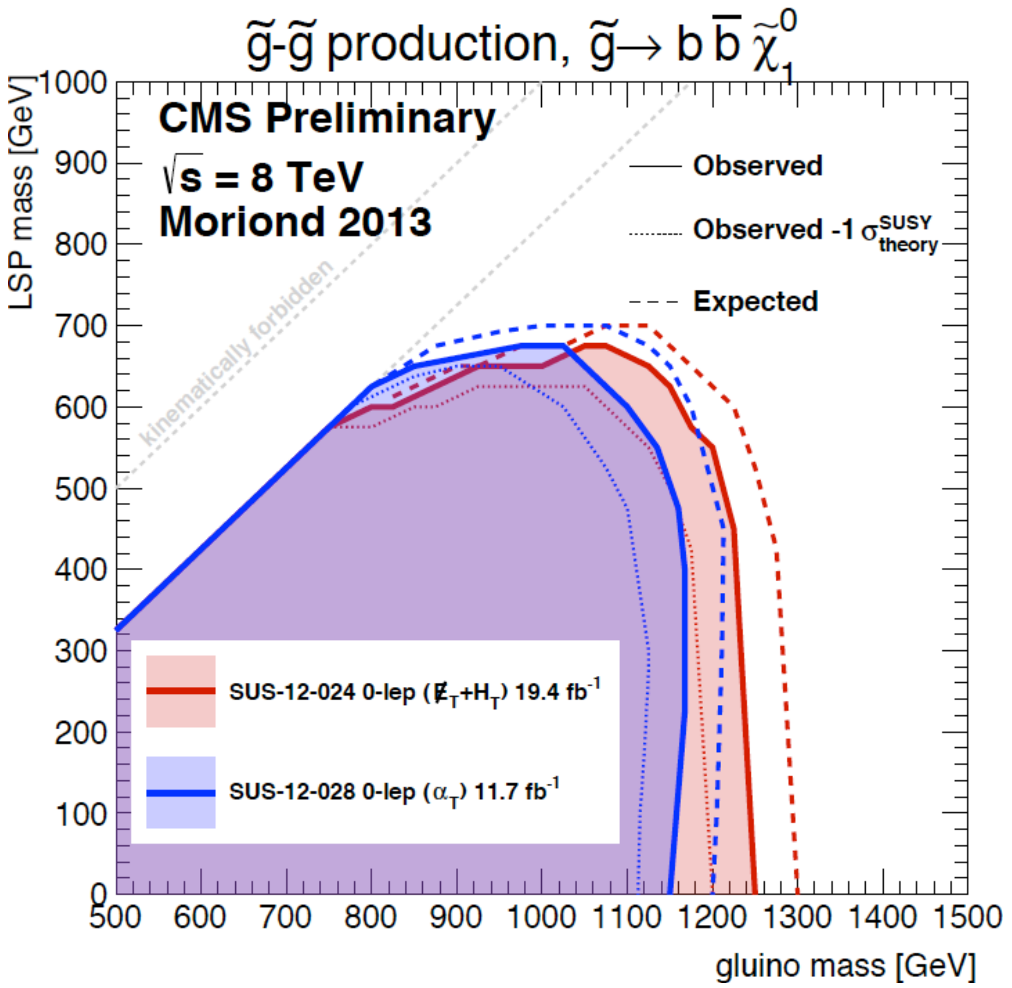
$\tilde{g}$ affects the stop masses

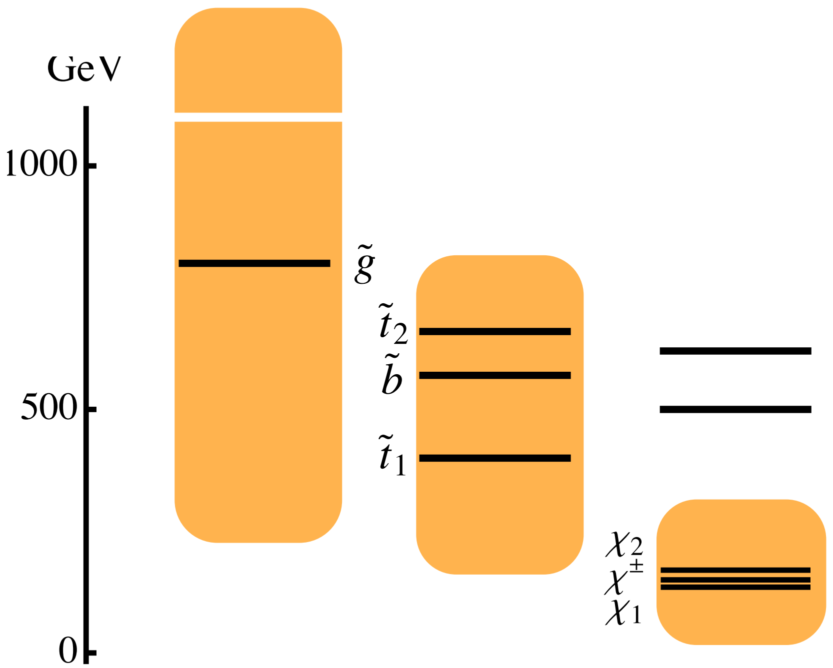
$\tilde{t}_1, \tilde{t}_2, \tilde{b}_L$ ⇔ strongest coupling to the Higgs system

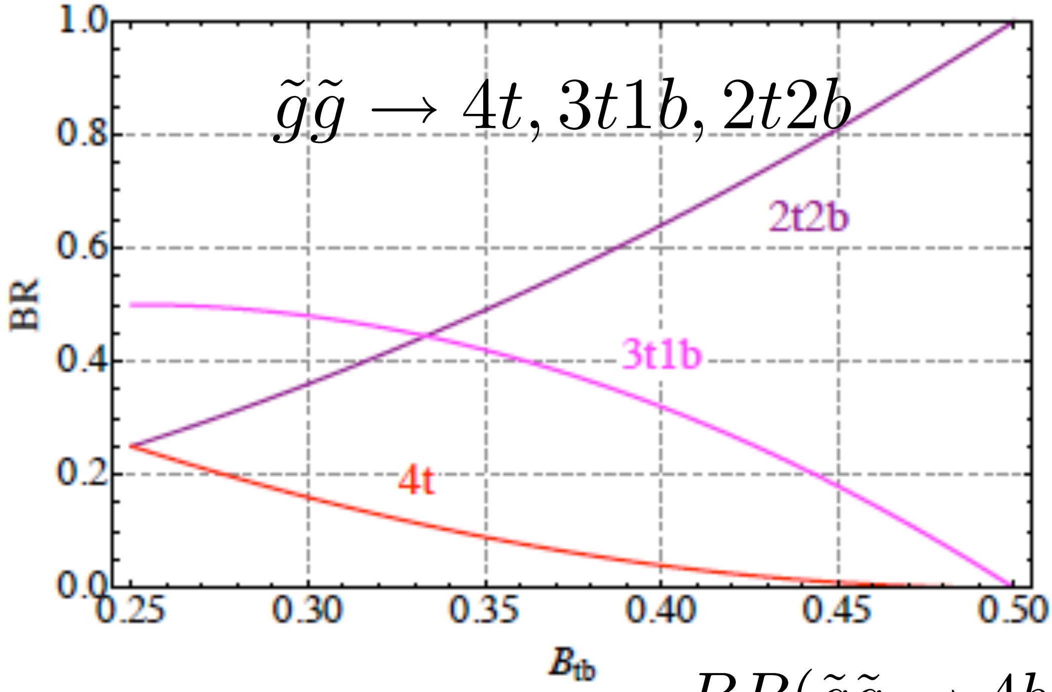
μ ⇔ $M_Z$ at tree level

orange areas indicative and dependent on how the Higgs boson gets its mass





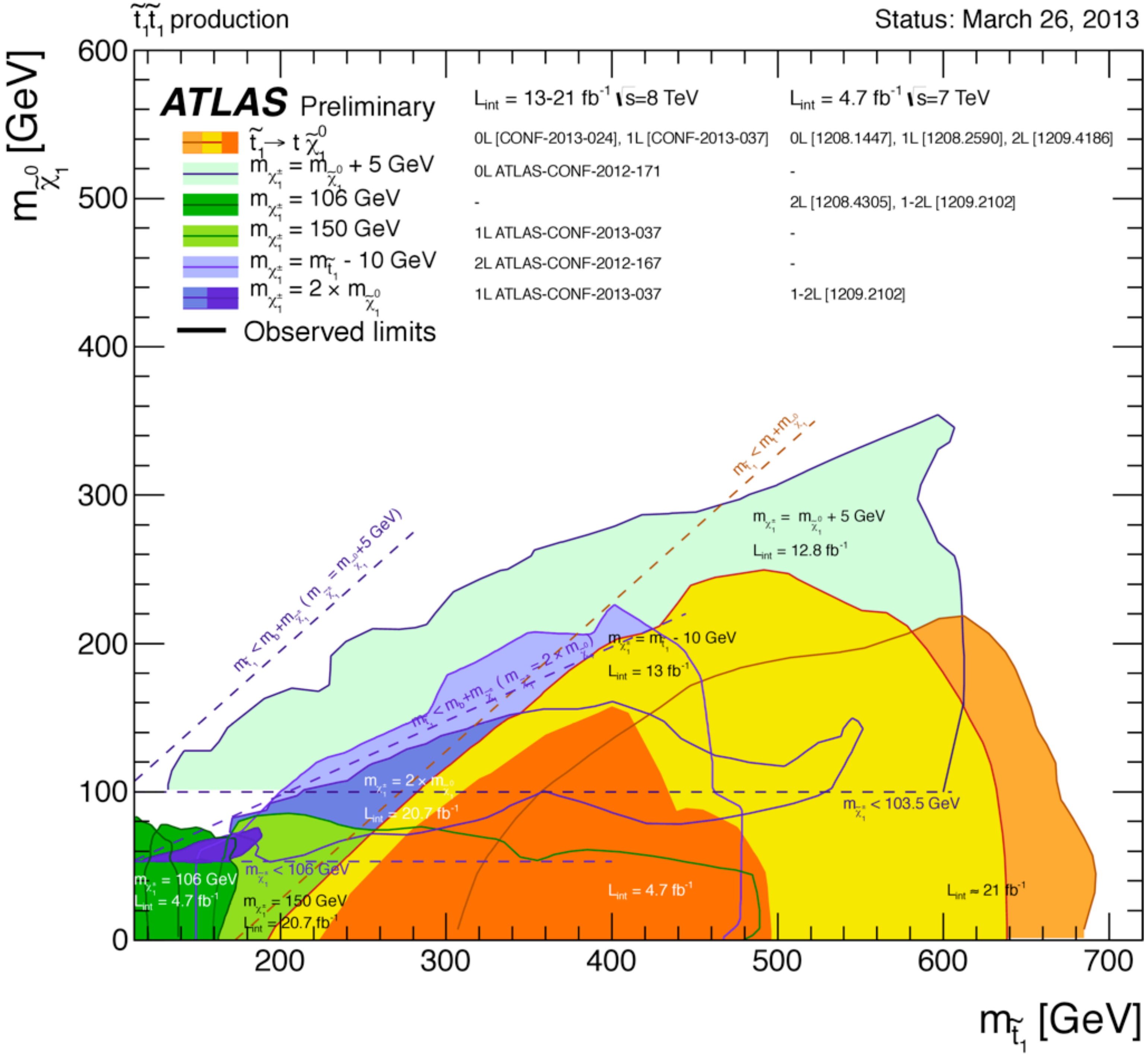


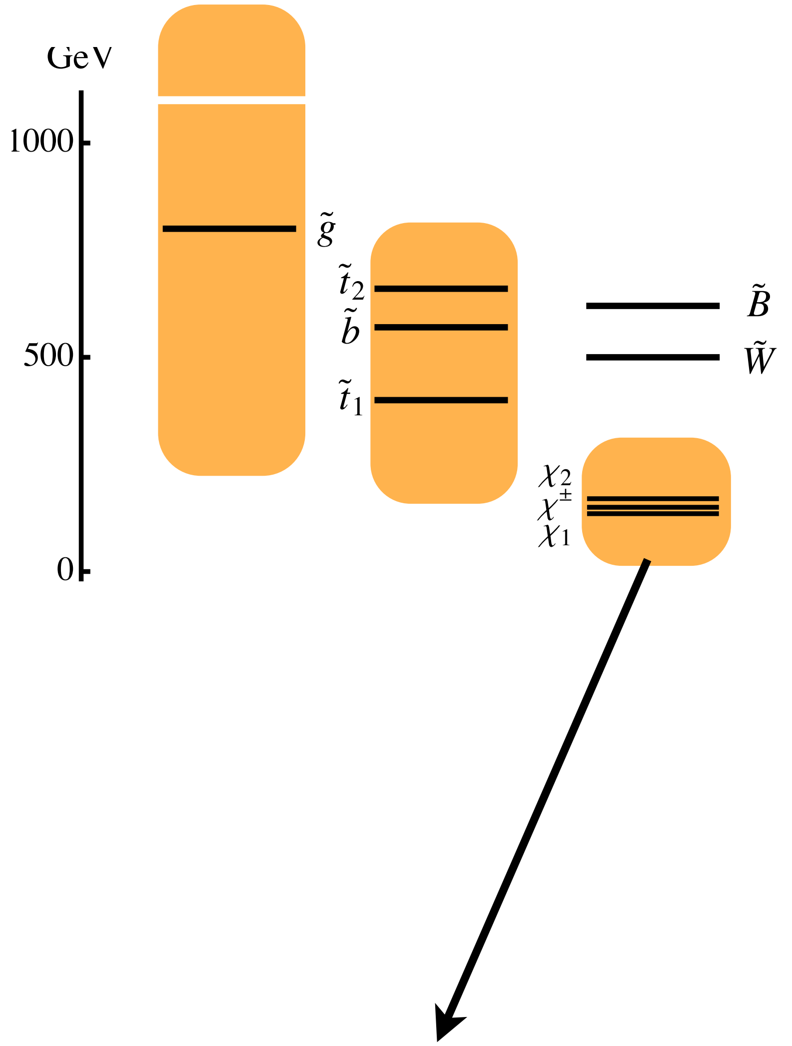


$$BR(\tilde g \tilde g \to 4b) \lesssim 4\%$$
$$(\tan\beta \lesssim 10)$$

"naively" $m_{\tilde g} \gtrsim 1300\ GeV$

"conservatively" $m_{\tilde g} \gtrsim 1000\ GeV$





$$m_{\chi_2} \approx m_{\chi^\pm} \approx m_{\chi_1}$$

"naively" $m_{\tilde{t}_1} \gtrsim 700\ GeV$

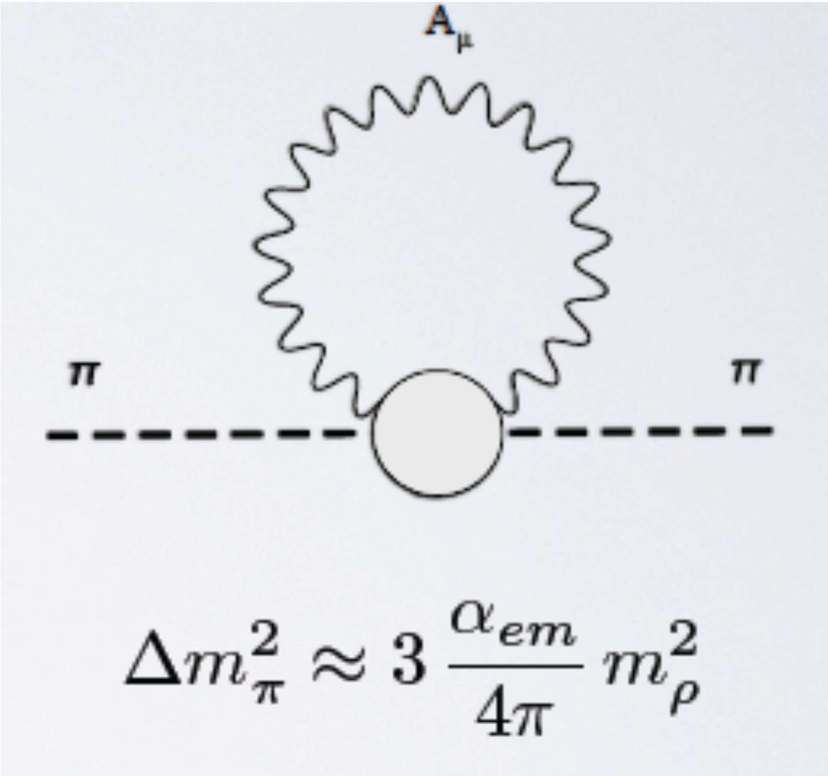
"conservatively" $m_{\tilde{t}_1} \gtrsim 200 \div 300\ GeV$ (with $m_\chi = 150 \div 250\ GeV$ )

# The Higgs boson as a pseudo-Goldstone boson

(hence a composite rather than a “fundamental” object)

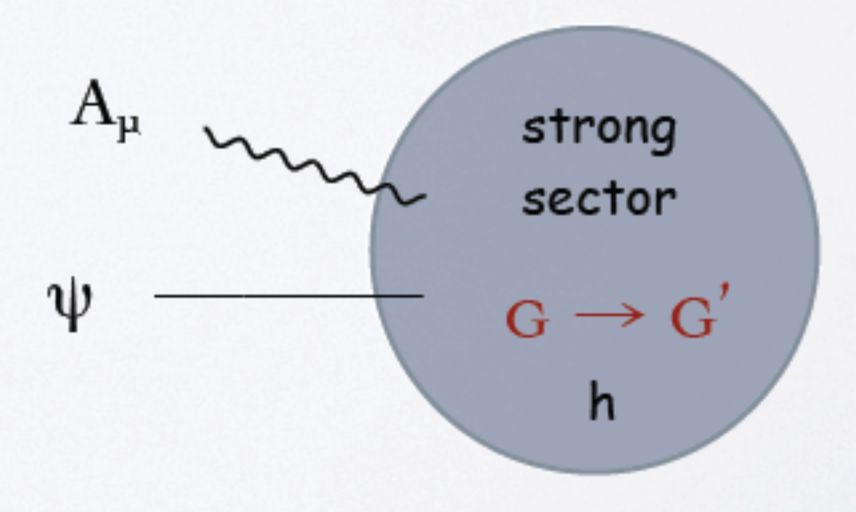
The pion as an analogy:

$$SU(2)_L \times SU(2)_R \Rightarrow SU(2)_I$$
$$\Delta m_\pi^2 = m_{\pi^+}^2 - m_{\pi^0}^2$$



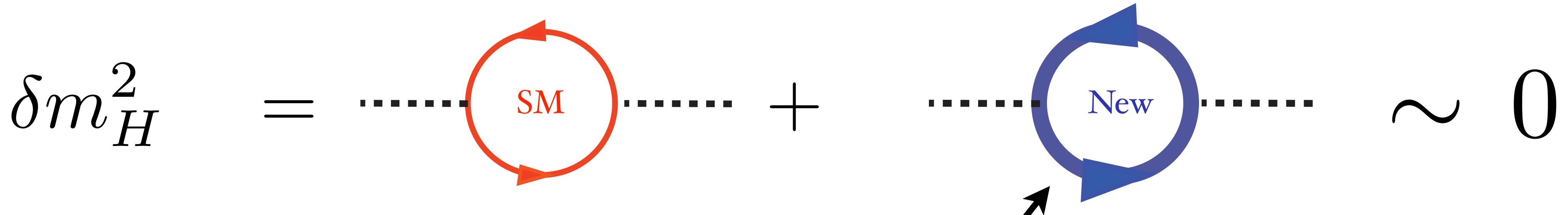
$$\Delta m_\pi^2 \approx 3\,\frac{\alpha_{em}}{4\pi}\,m_\rho^2$$

A new strong sector
at the TeV scale



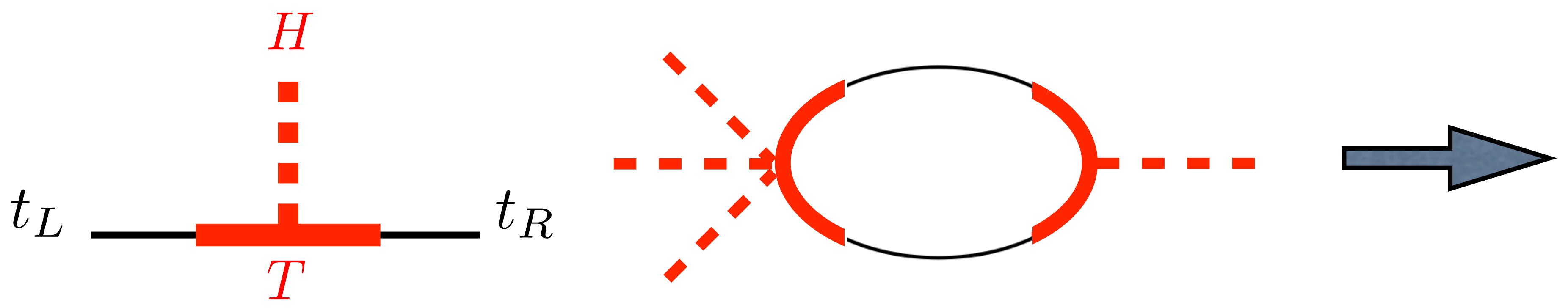
Like the pion in QCD, the Higgs boson as a quasi GB
of a spontaneously broken global symmetry at the TeV

# More in detail



Heavy “composite” fermions

Heavy “composite” fermion mass



$$m_h \sim m_t \frac{M_T}{\pi f}$$

symmetry breaking scale

Most common:

$$Q = \begin{pmatrix} T \\ B \end{pmatrix}, \quad X = \begin{pmatrix} X_{5/3} \\ T_{2/3} \end{pmatrix}, \quad \tilde{T}$$

Current searches exclude masses below 500-800 GeV, depending on the charge

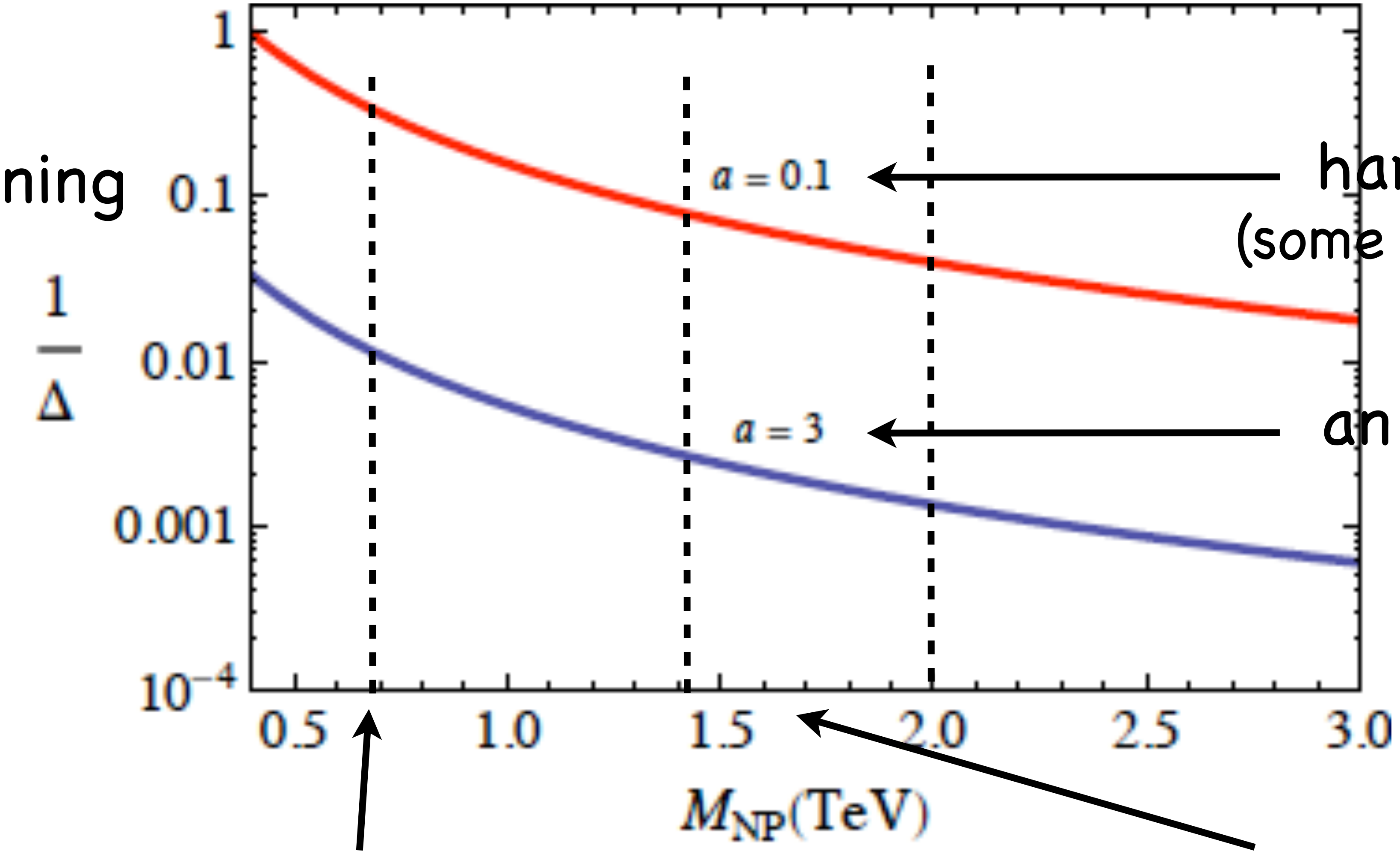
# A quantitative measure (!?) of naturalness

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

model dependent

a measure of fine tuning
(which exist in nature)

fine tuning



hard to achieve
(some NMSSM gets close)

an indicative MSSM

≈ LHC now

≈ LHC14 (?)

# Last but not least: one or more Higgs bosons?

The pro's for one:

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 $\lambda_{ij}$

4. a single tuning, in case

None is better, which often demands more Higgs boson

# Two ways to attack the problem

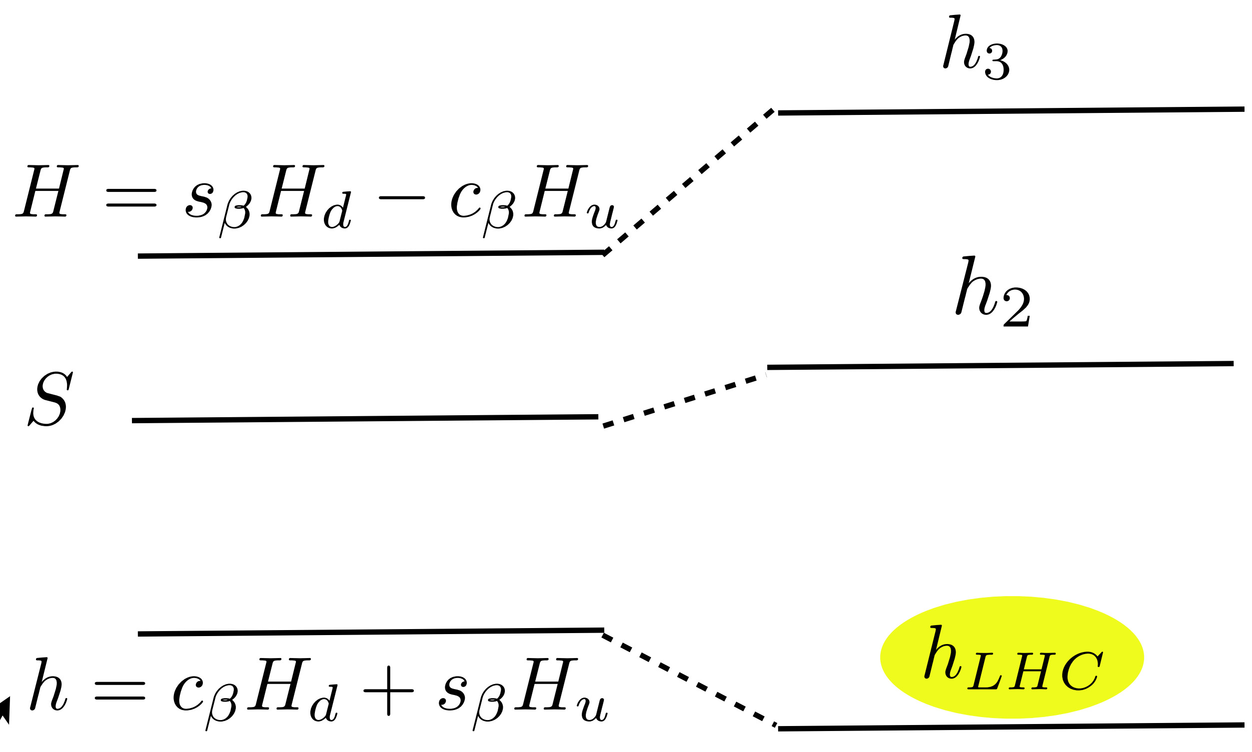
⇒ By direct search $pp \to h_{\neq LHC} + X$

→ decay products

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

(the NMSSM example)

$\lambda S H_u H_d$



$h_3$

$H = s_\beta H_d - c_\beta H_u$

$h_2$

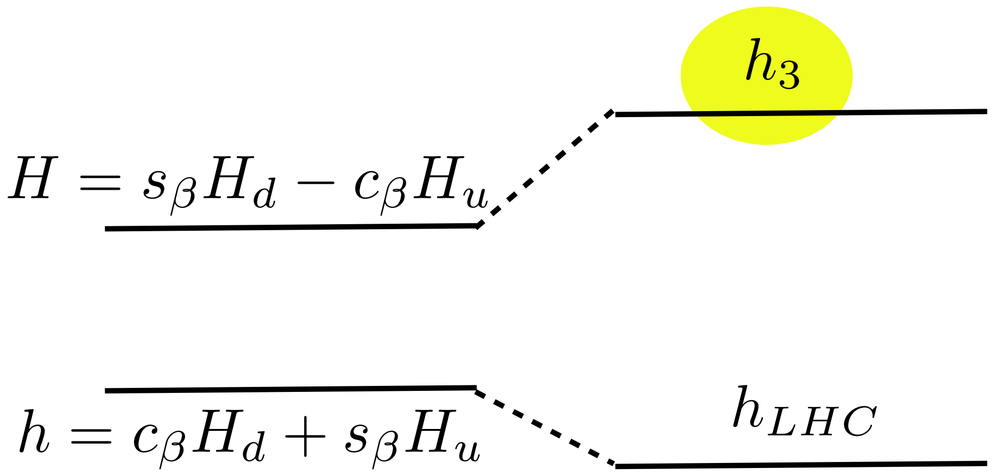
$S$

$h_{LHC}$

$h = c_\beta H_d + s_\beta H_u$

has SM properties

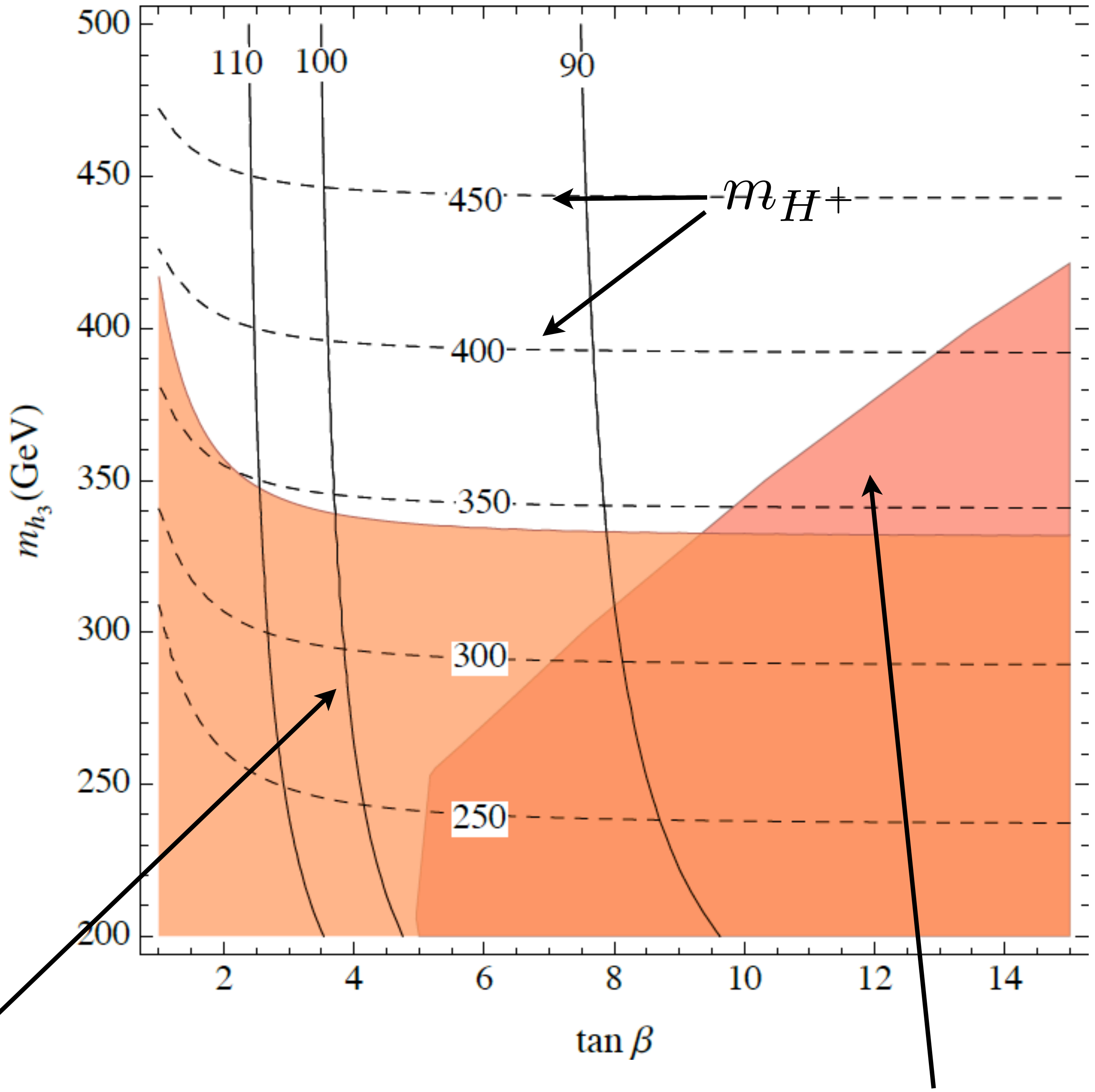
# Current status of the MSSM



$$H = s_\beta H_d - c_\beta H_u$$

$$h = c_\beta H_d + s_\beta H_u$$

MSSM at variable $\Delta_t$

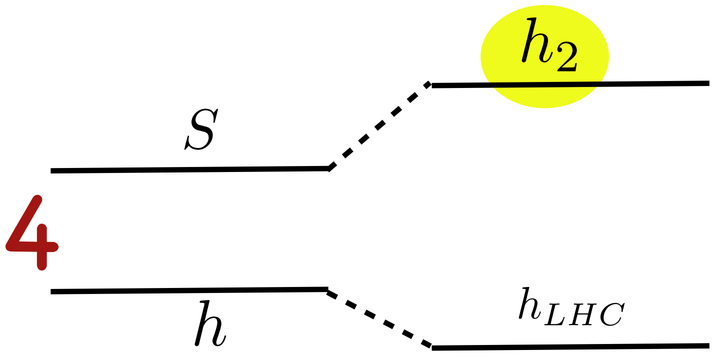


"excluded" by $h_{LHC}$ -signal strenghts

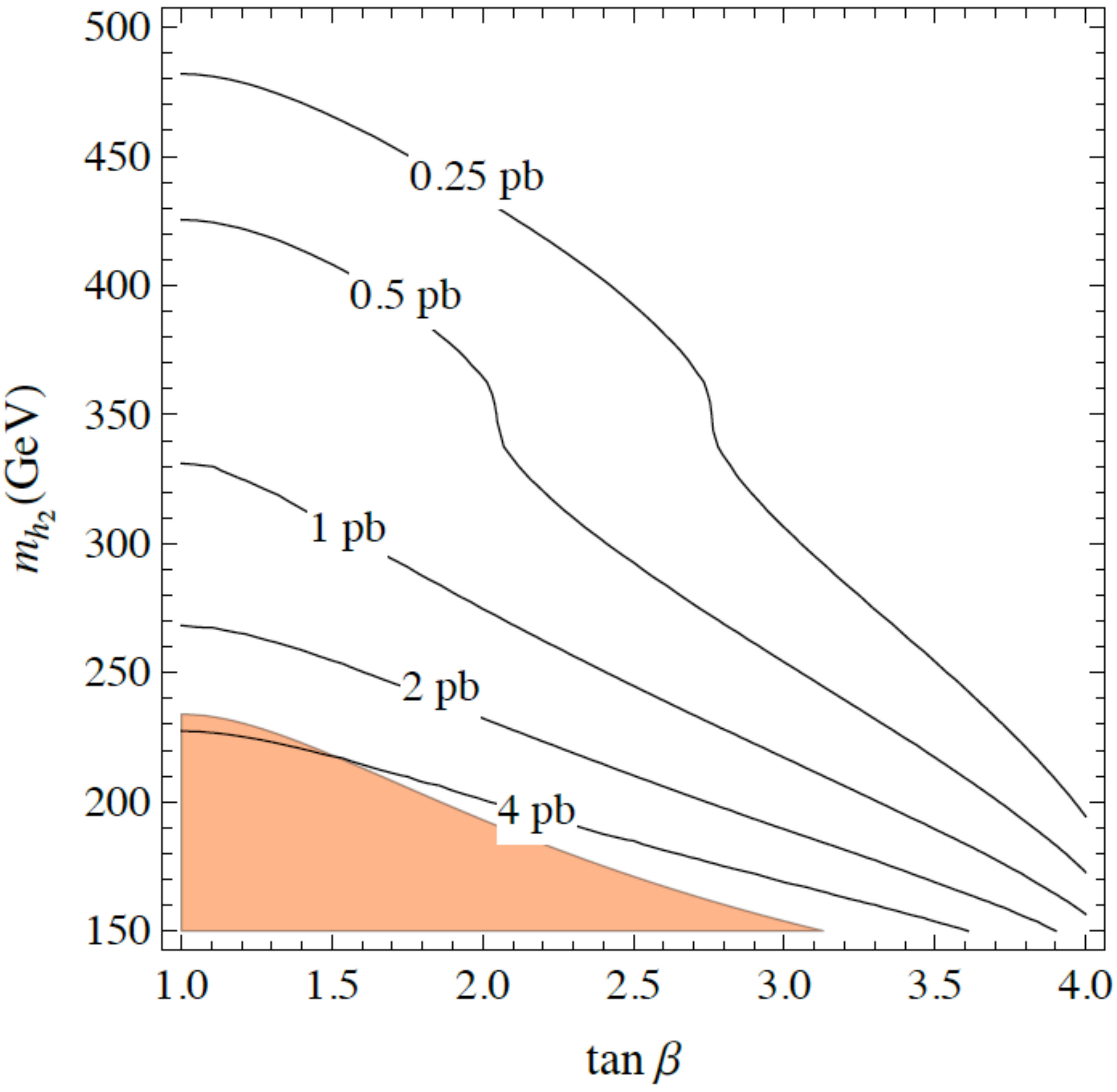
"excluded" by $h_3, A \to \tau\tau$

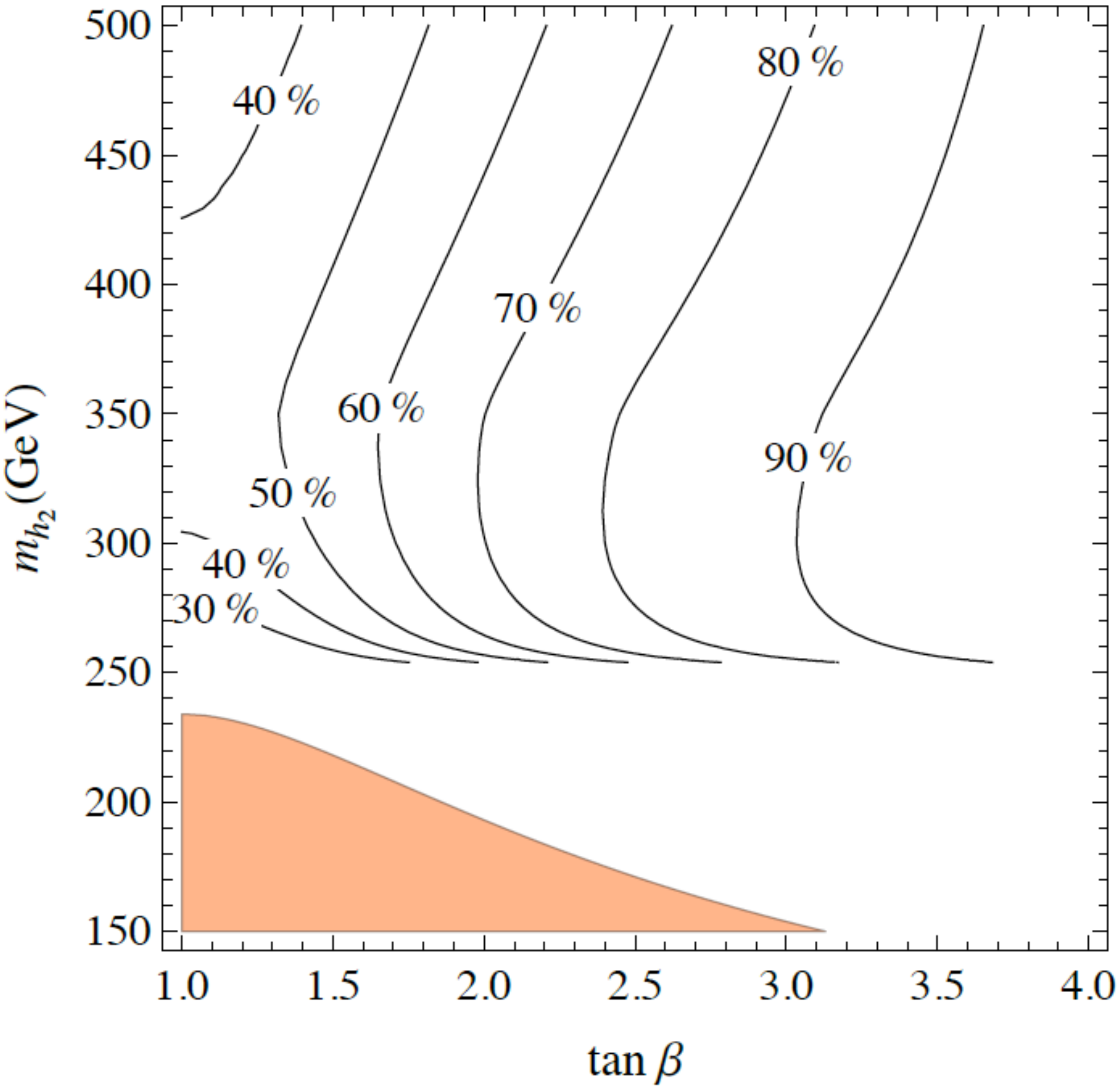
B, Buttazzo, Kannike, Sala, Tesi 2013

# NMSSM: Direct search at LHC14



$\lambda = 0.8$

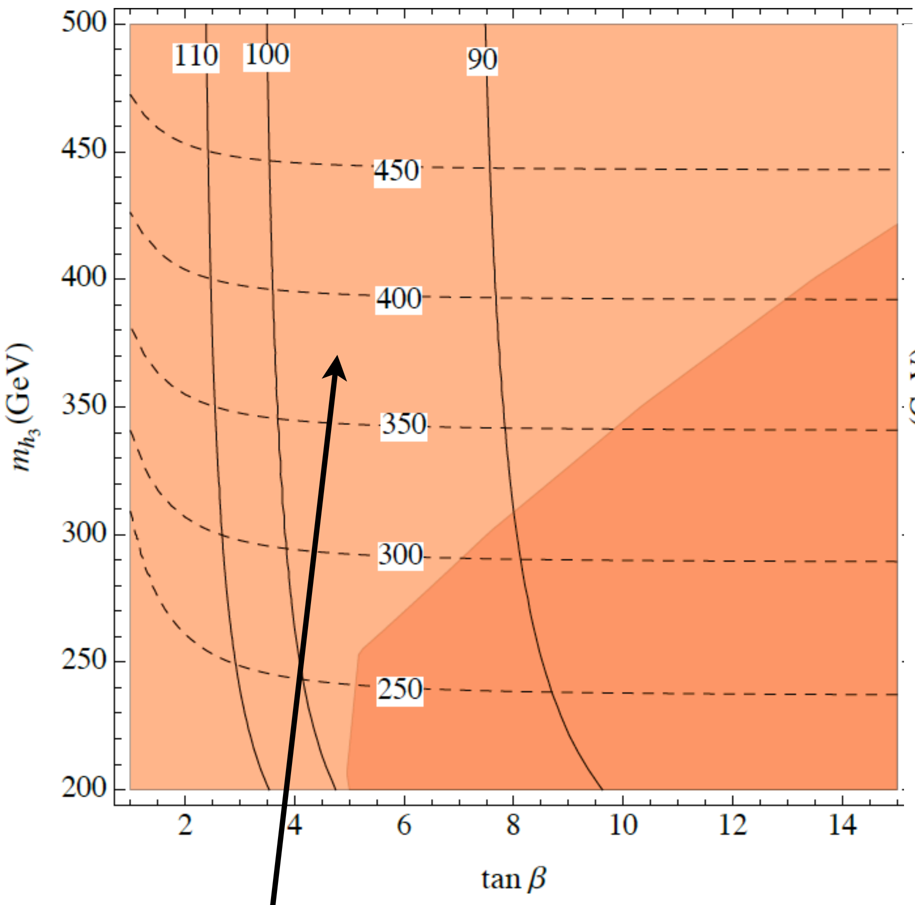

$\sigma(gg \to h_2)$


$BR(h_2 \to h_1 h_1)$

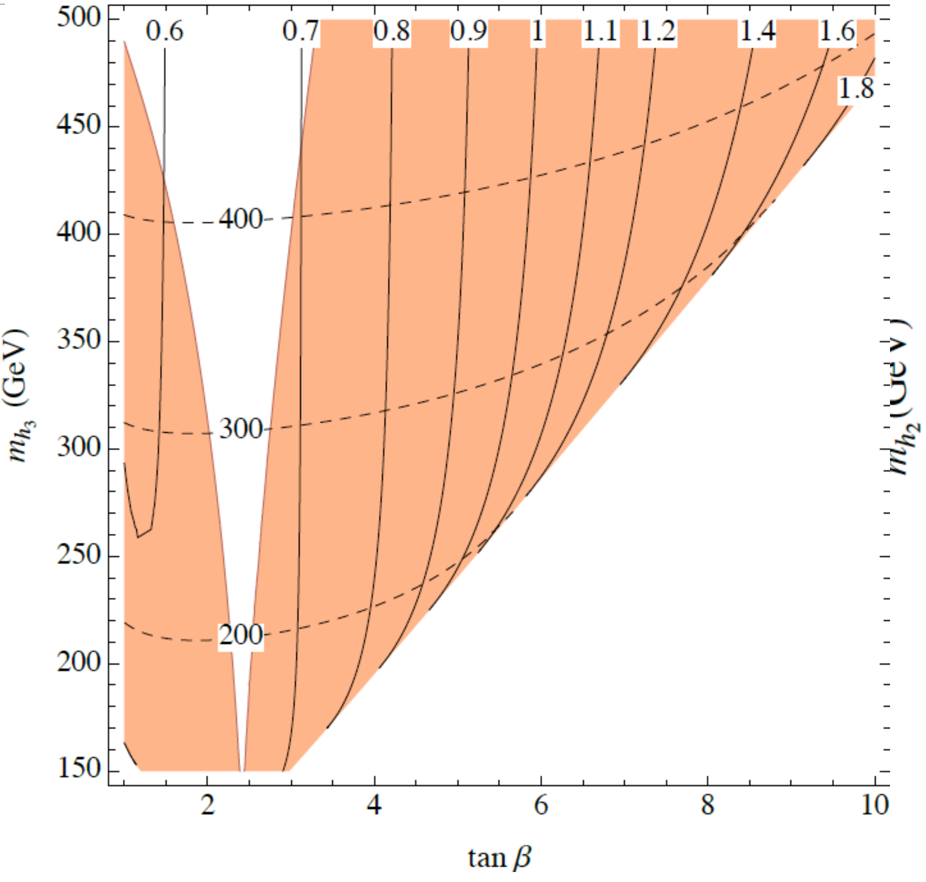
(changes in the $h_1$ self coupling by factors 3-4 possible)

# A projection from the measurements of the signal strenghts of $h_{LHC}$

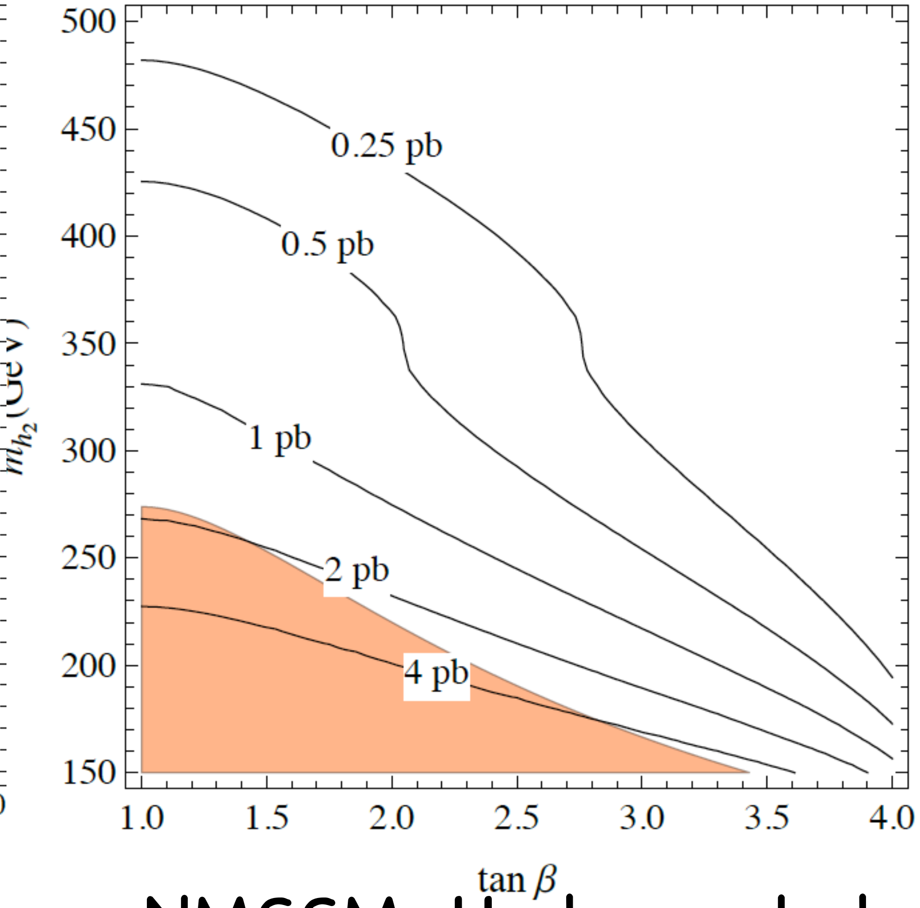
LHC14 at $300 fb^{-1}$ with ATLAS/CMS projected errors



MSSM



NMSSM, S-decoupled

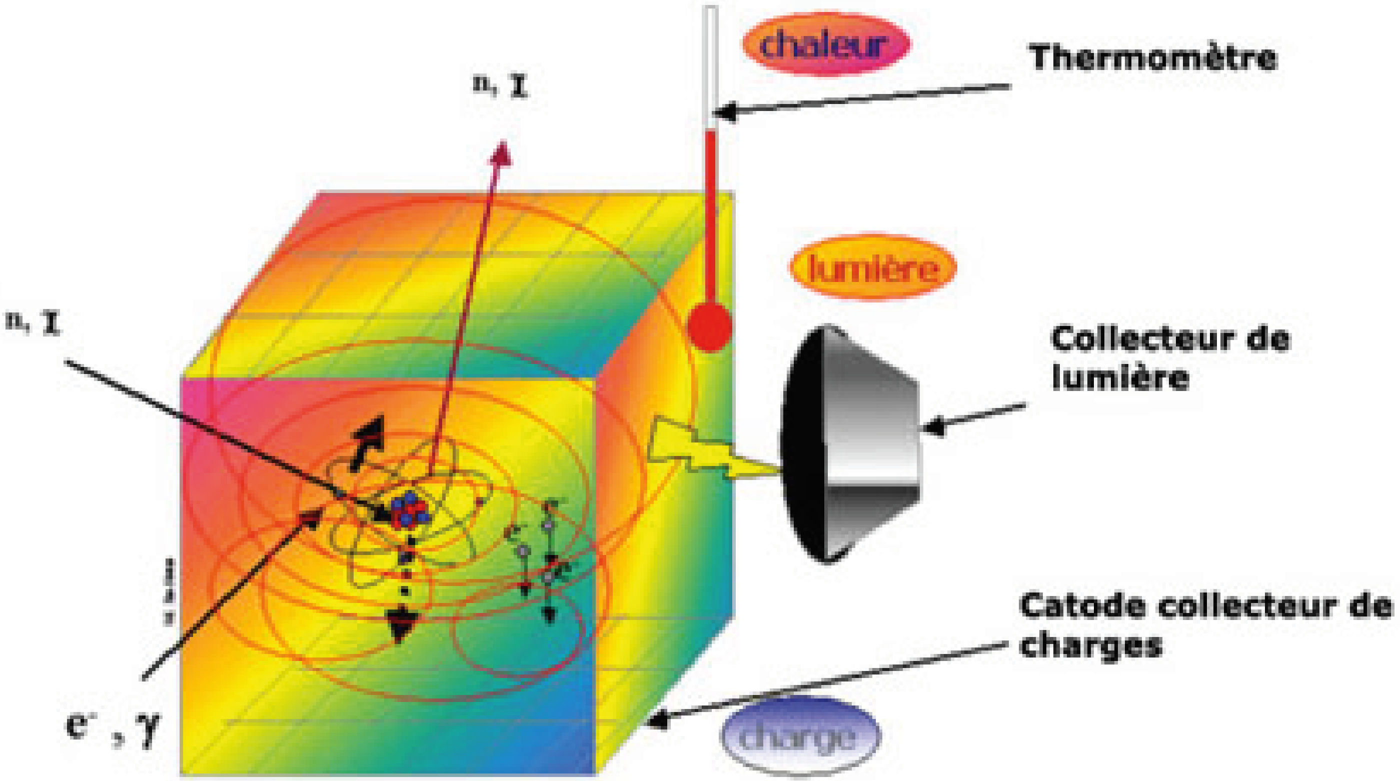


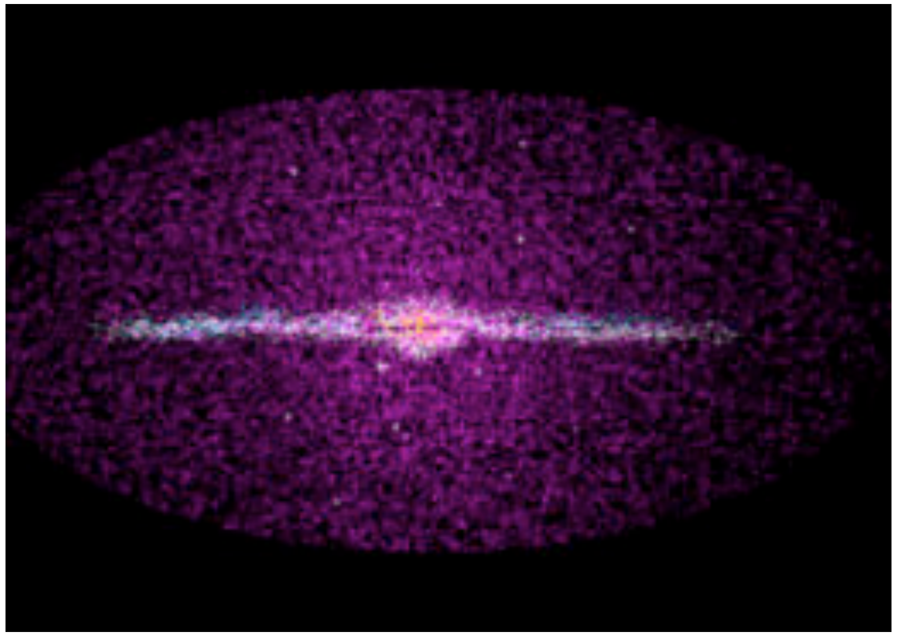
NMSSM, H-decoupled

The sensitivity region extends up to about 1 TeV for $m_{h_2}$

# The direct search for Dark Matter

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





$$Z_\mu \bar{\Psi}_M \gamma_\mu \Psi_M = 0$$

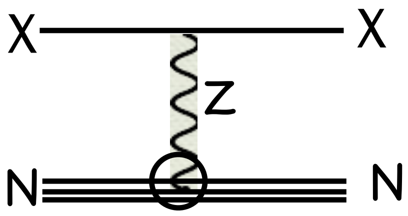
$$Z_\mu \bar{\Psi}_M \gamma_\mu \gamma_5 \Psi_M \neq 0$$

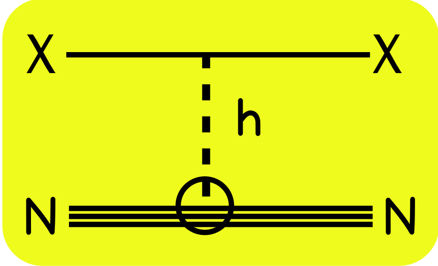
# DM searches and the Higgs boson

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

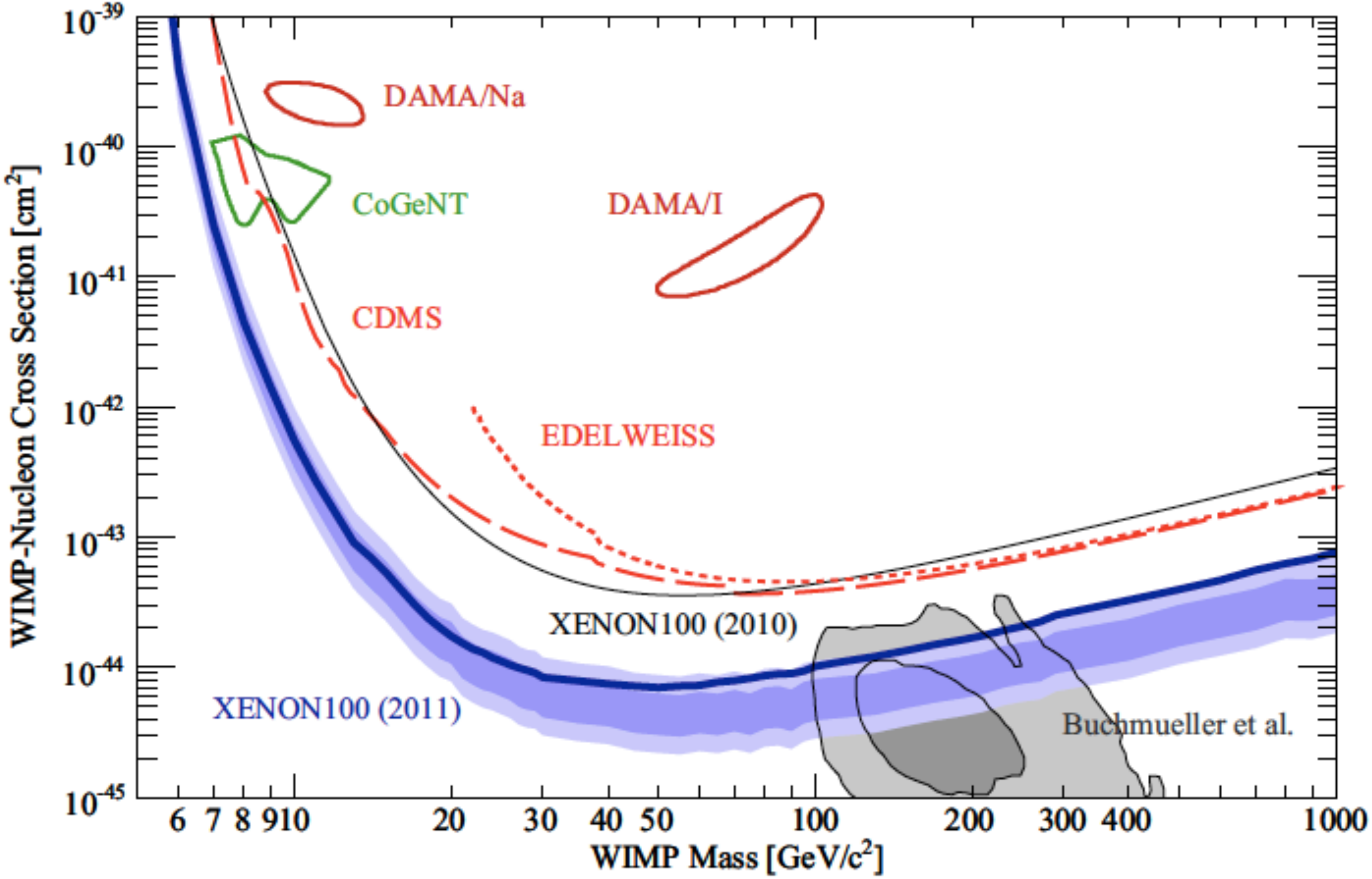
3 events/1.8 backgd

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





exclusion by XENON100 (100 days x 48 kgs)



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

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

# Conclusion

**1. The discovery of the Higgs boson:**

might be BOTH the coronation of the Standard Theory
AND
a first step towards unexplored territory

**2. Natural or unnatural theories?**

before accepting a shift of paradigm,
useful to be patient and careful

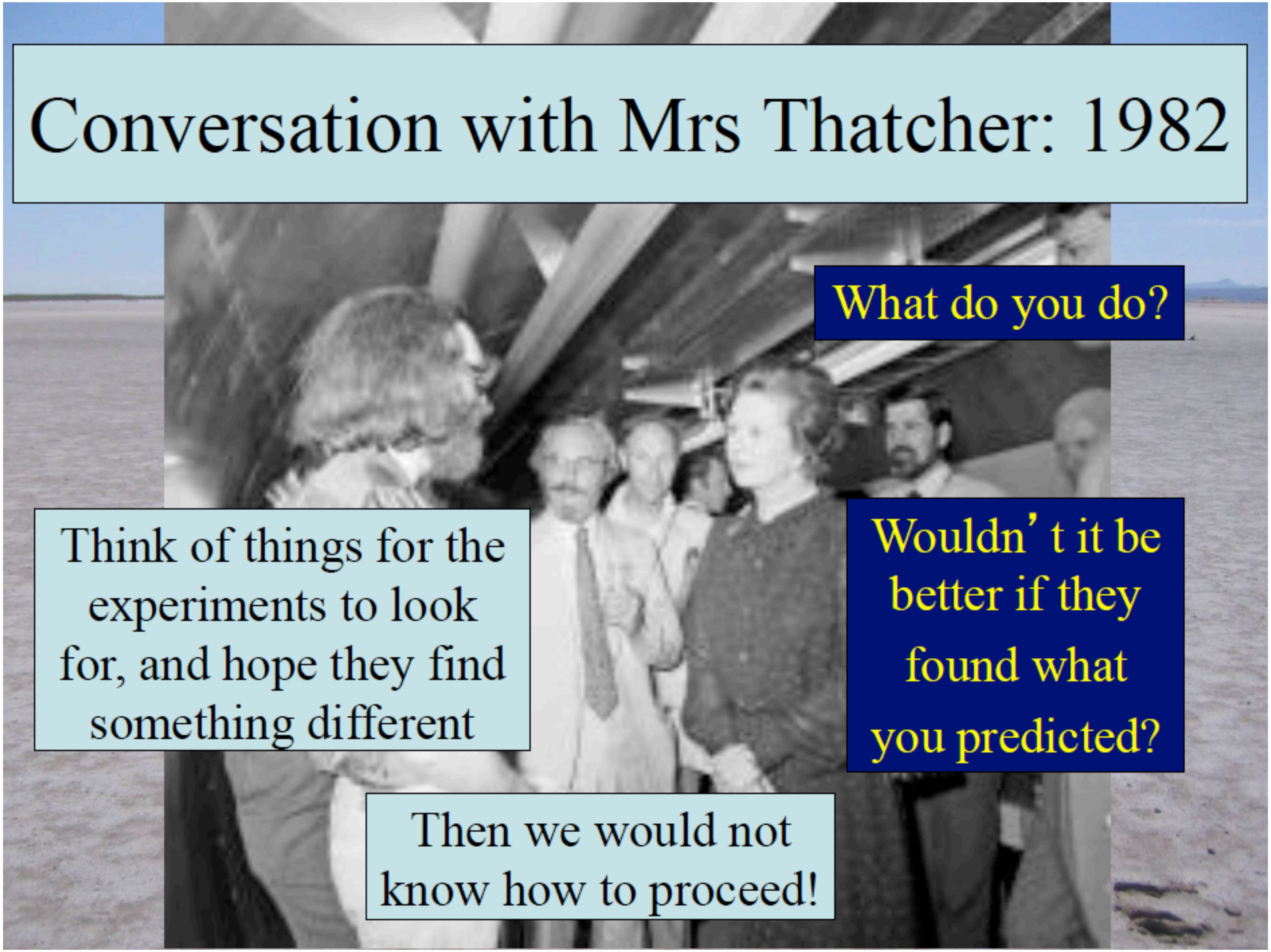
**3. One or more Higgs bosons?**

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 new key data

# Conversation with Mrs Thatcher: 1982



What do you do?

Think of things for the experiments to look for, and hope they find something different

Wouldn't it be better if they found what you predicted?

Then we would not know how to proceed!

Guess who is Mrs. Tatcher and who is the other guy

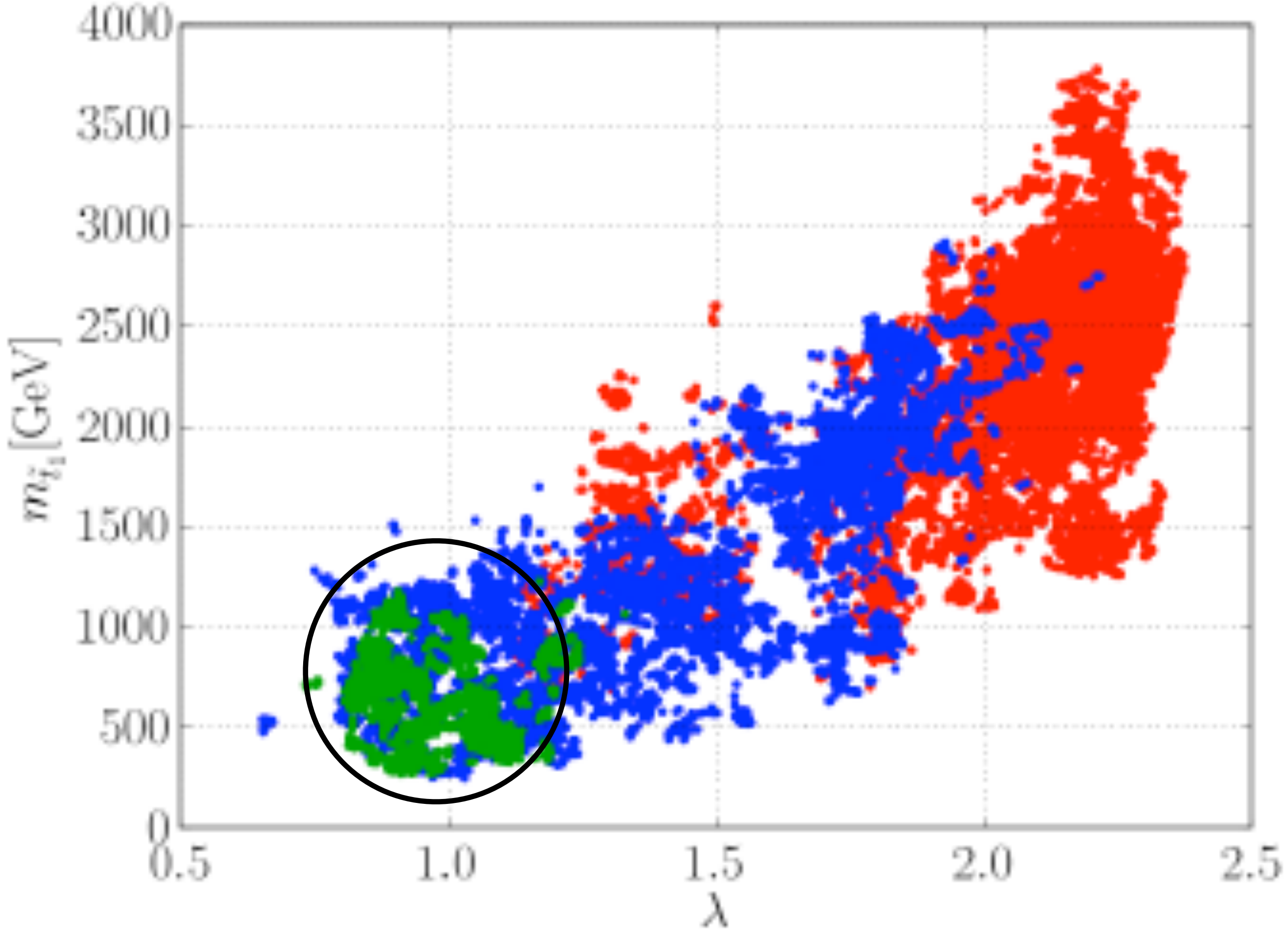
# NMSSM $\Delta f = \lambda H_u H_d$

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 $\lambda \gtrsim 1$ and moderate $\tan\beta$

$$\frac{dv^2}{dm_{H_u}^2}|_{NMSSM} \approx \frac{\kappa}{\lambda^3}\cot 2\beta \quad \text{versus} \quad \frac{dv^2}{dm_{H_u}^2}|_{MSSM} \approx \frac{4}{g^2}$$



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

# Can the extra Higgs bosons of the NMSSM be the lightest new particles around?

⇒ Assume a negligibly small CPV in the Higgs sector

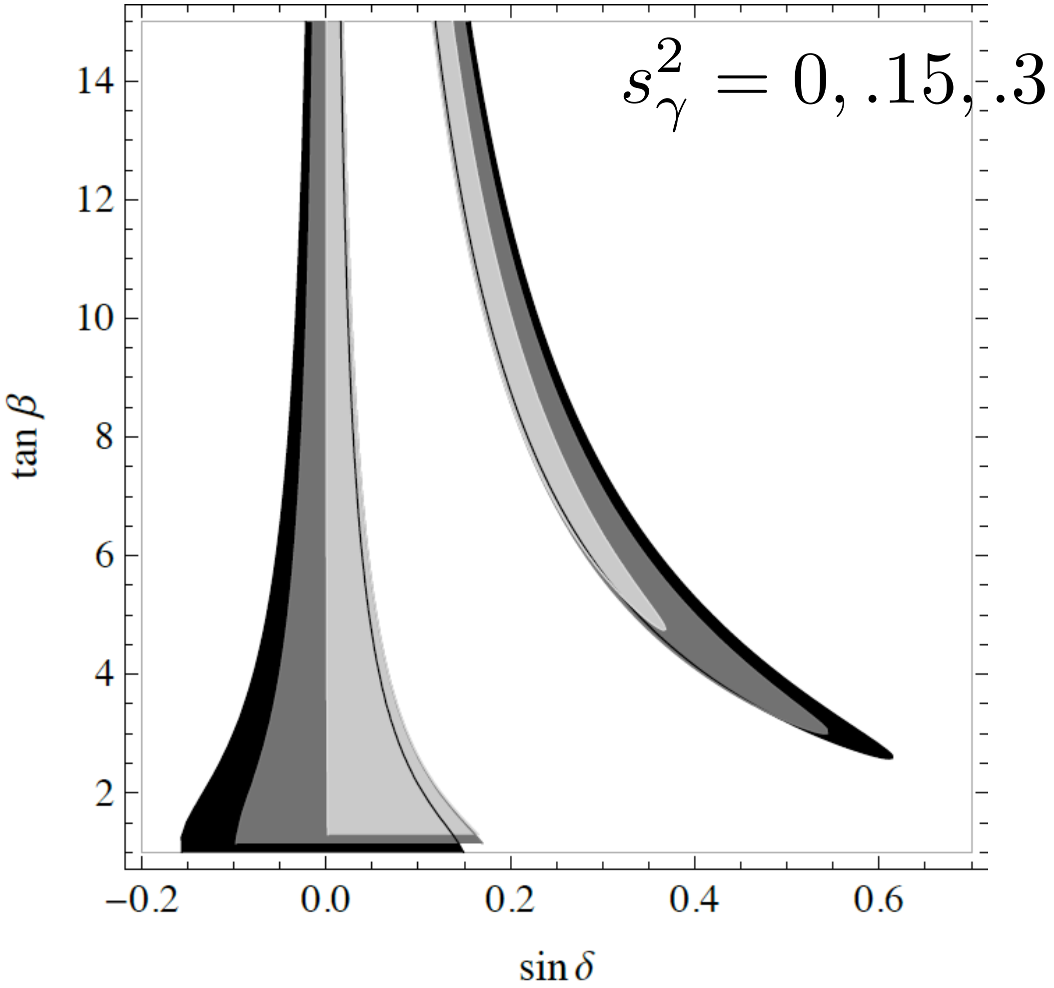
$$\mathcal{H} \equiv (H_d, H_u, S)^T = R^{12}_{\alpha} R^{23}_{\gamma} R^{13}_{\sigma} (h_3, h_1, h_2)^T \equiv R\, \mathcal{H}_{\rm ph}$$

⇒ Take $h_1 = h_{LHC}$ with $m_{h_1} > m_{h_2}, m_{h_3}$

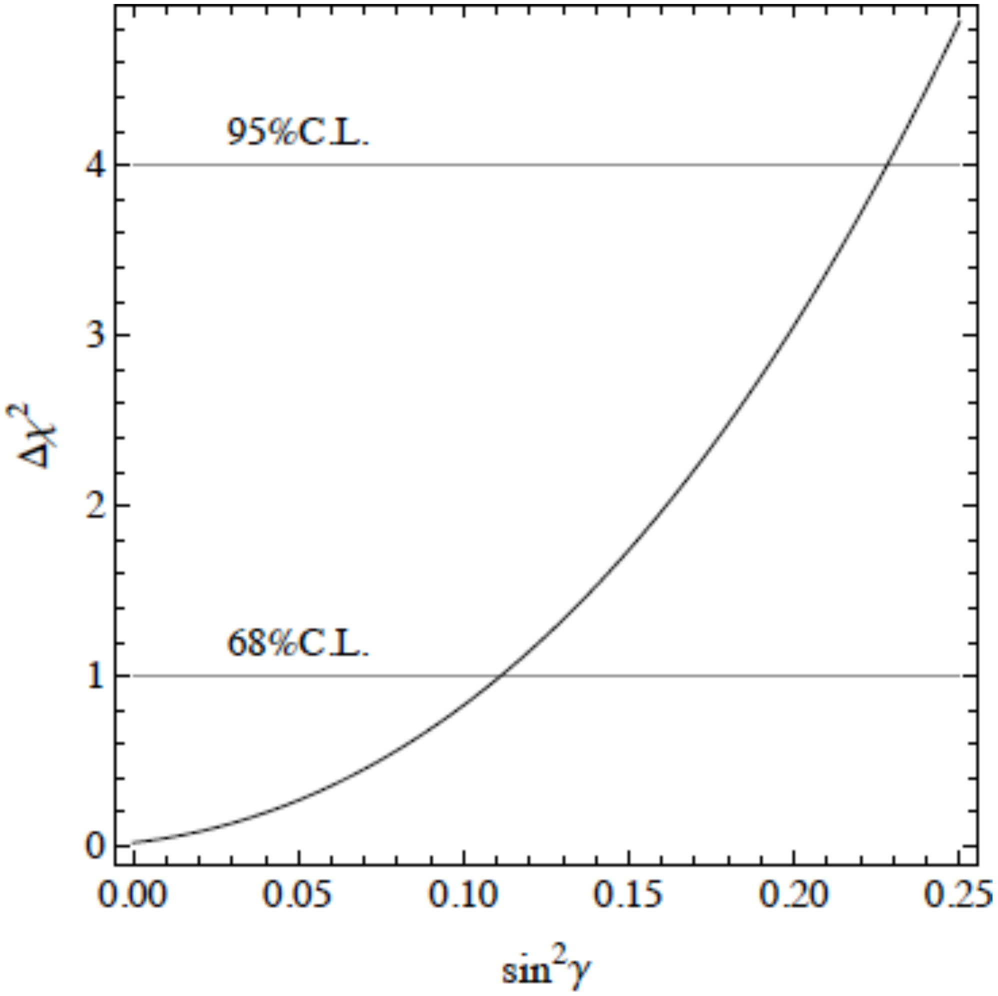
$$h_1 = c_\gamma(-s_\alpha H_d + c_\alpha H_u) + s_\gamma S$$

⇒ No susy loops nor invisible decays, like $h_1 \to \chi\chi$

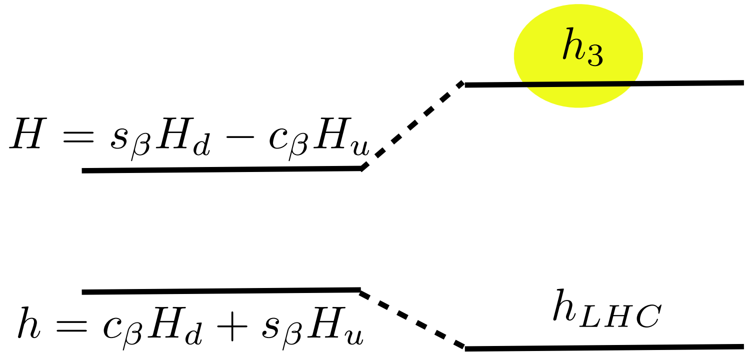
95%CL on $\delta = \alpha - \beta + \pi/2$

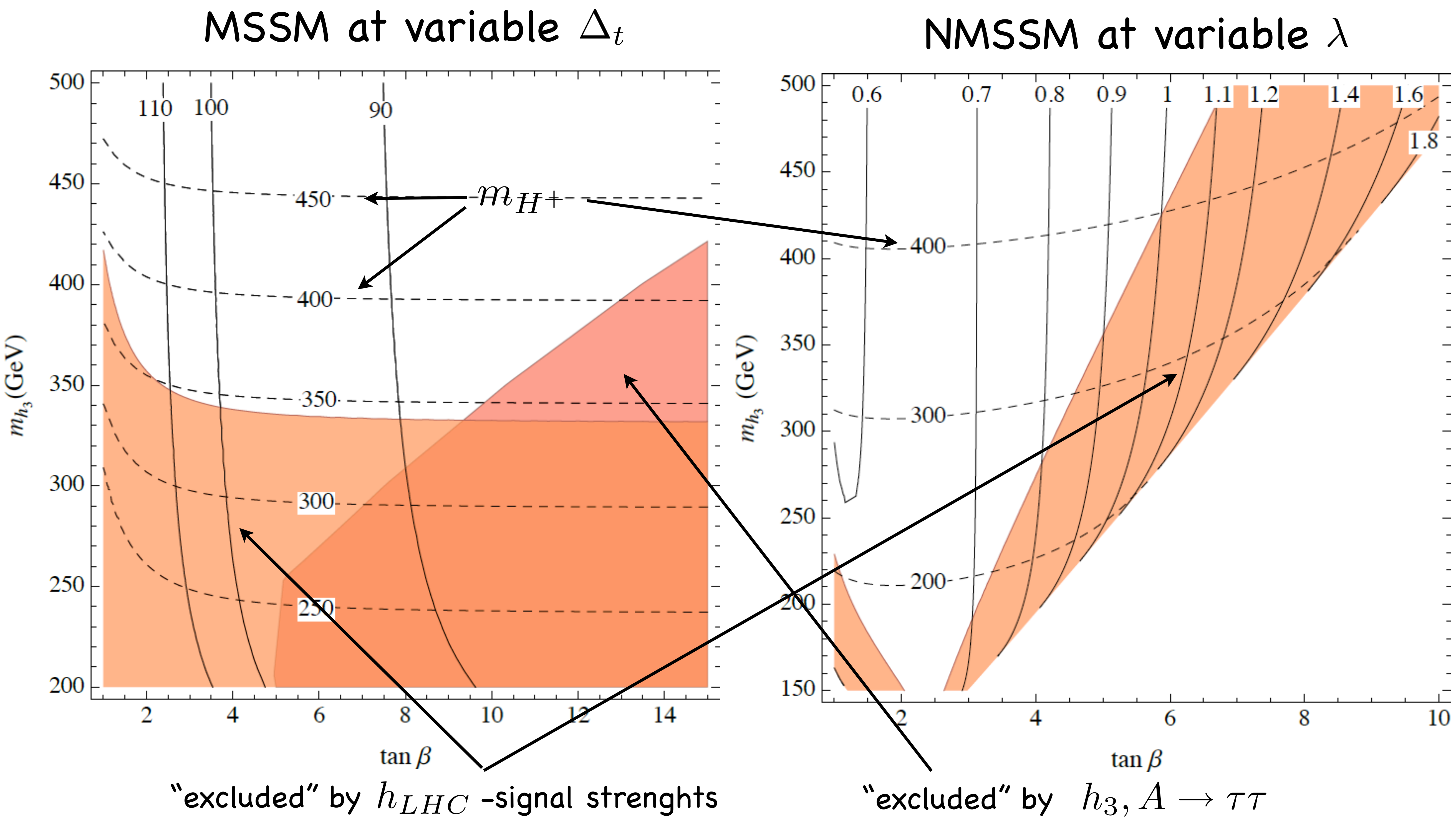


95%CL on $\gamma$ $(\delta = 0)$



# Current status




MSSM at variable $\Delta_t$

NMSSM at variable $\lambda$

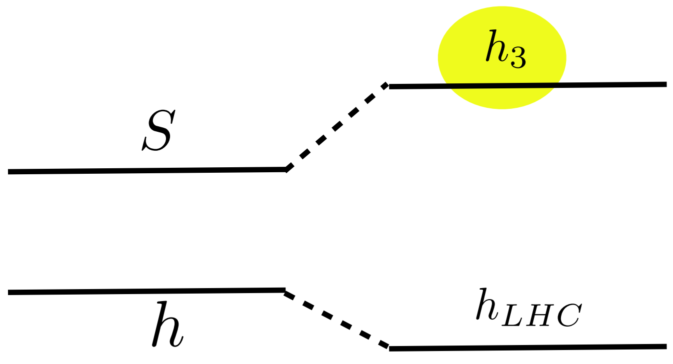
$m_{H^+}$

"excluded" by $h_{LHC}$ -signal strenghts

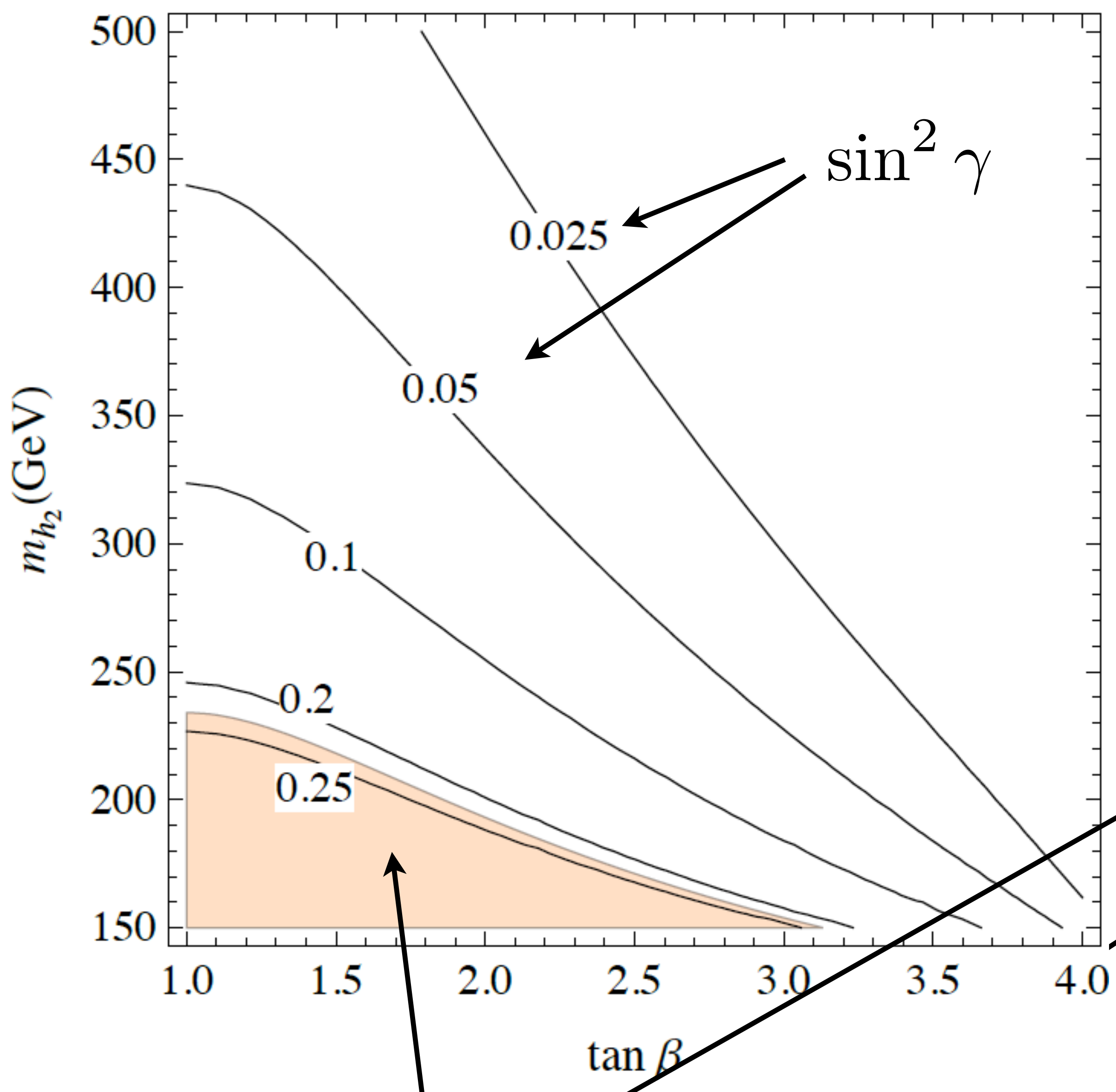
"excluded" by $h_3, A \to \tau\tau$

B, Buttazzo, Kannike, Sala, Tesi 2013

# H-decoupled

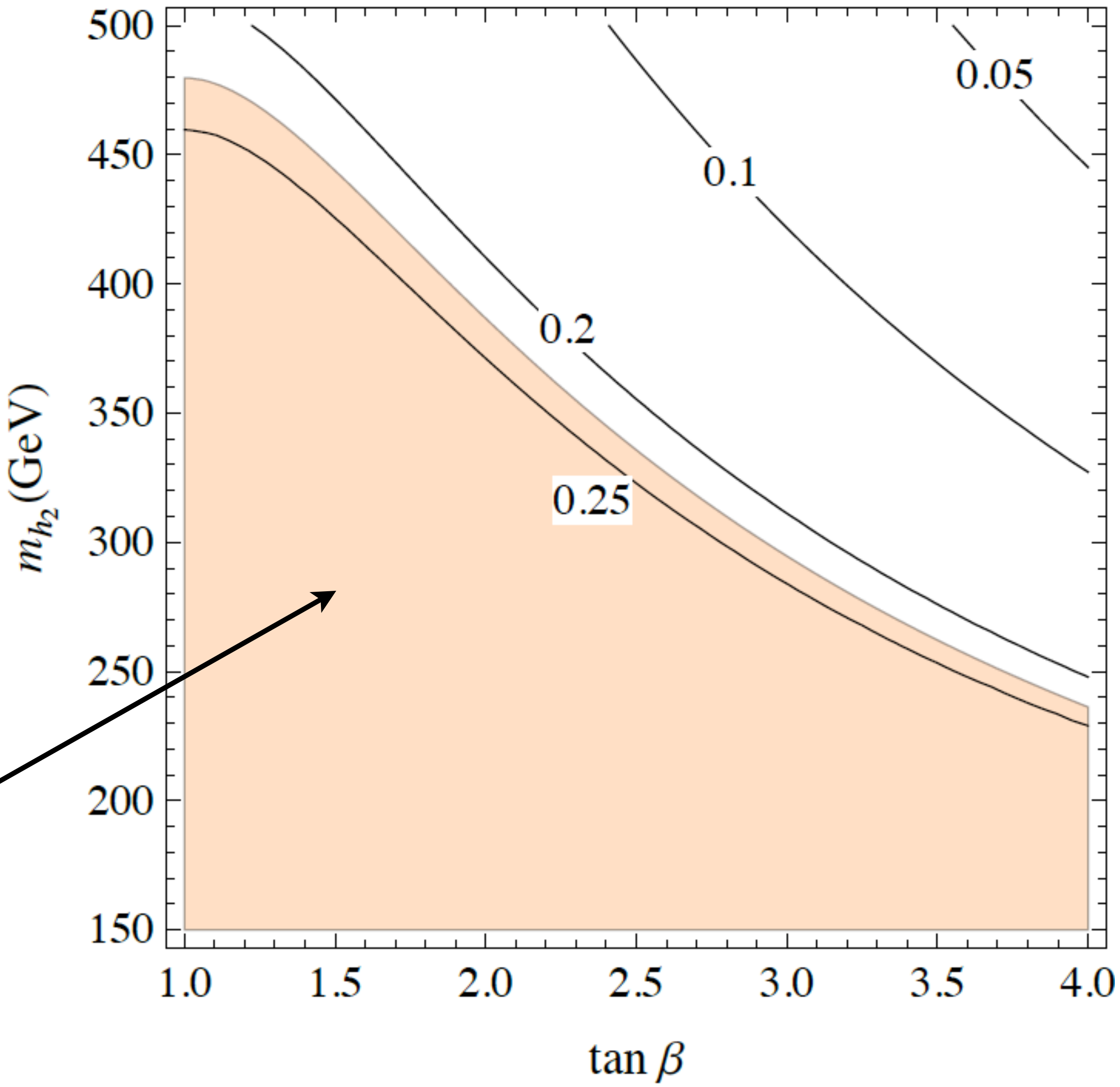


$\lambda = 0.8$



$\sin^2\gamma$

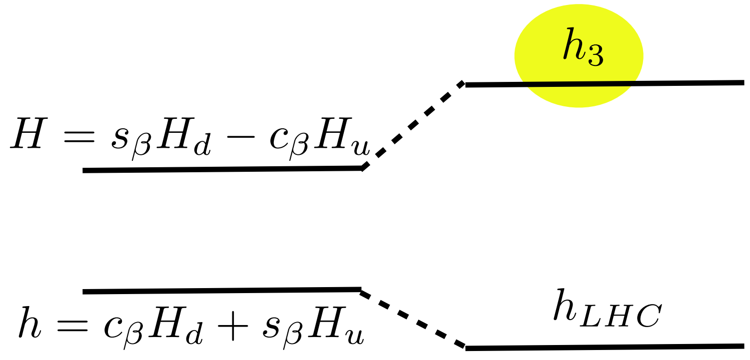
$\lambda = 1.4$



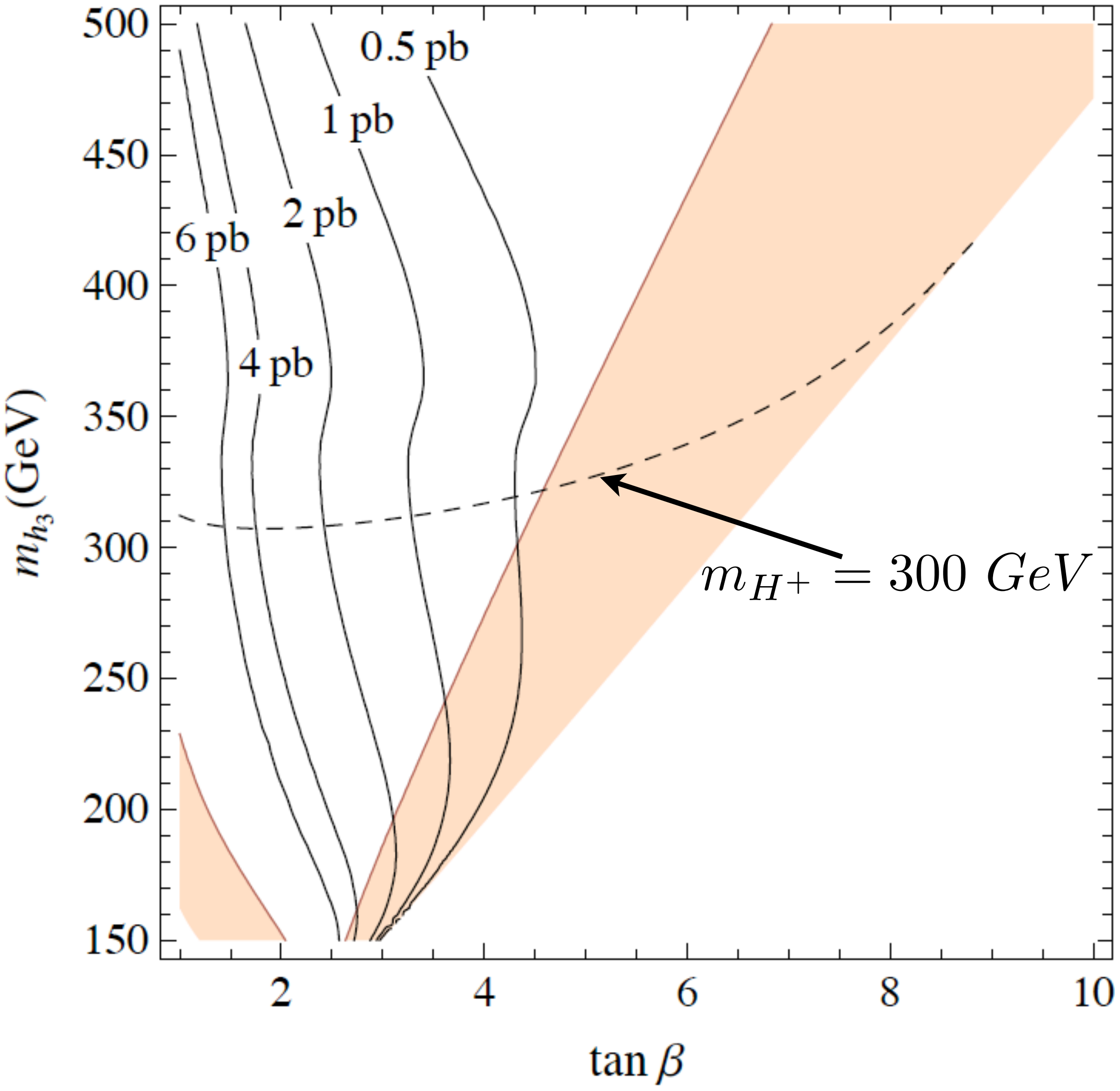
$\Delta_t \leq 75\ GeV$ almost irrelevant

“excluded” by $h_{LHC}$ -signal strenghts

# S-decoupled at LHC14

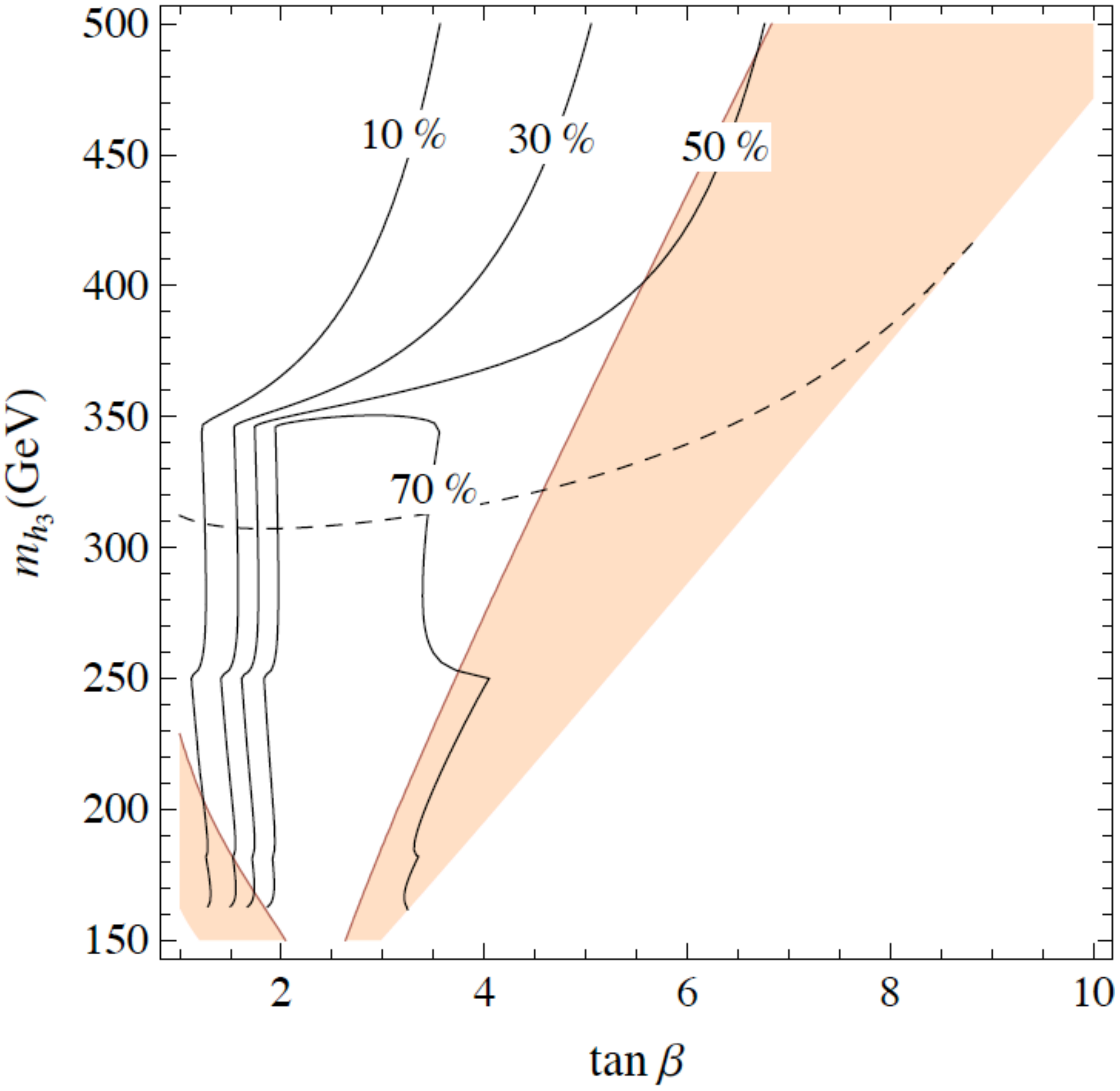


$\sigma(gg \to h_3)$



$m_{H^+} = 300\ GeV$

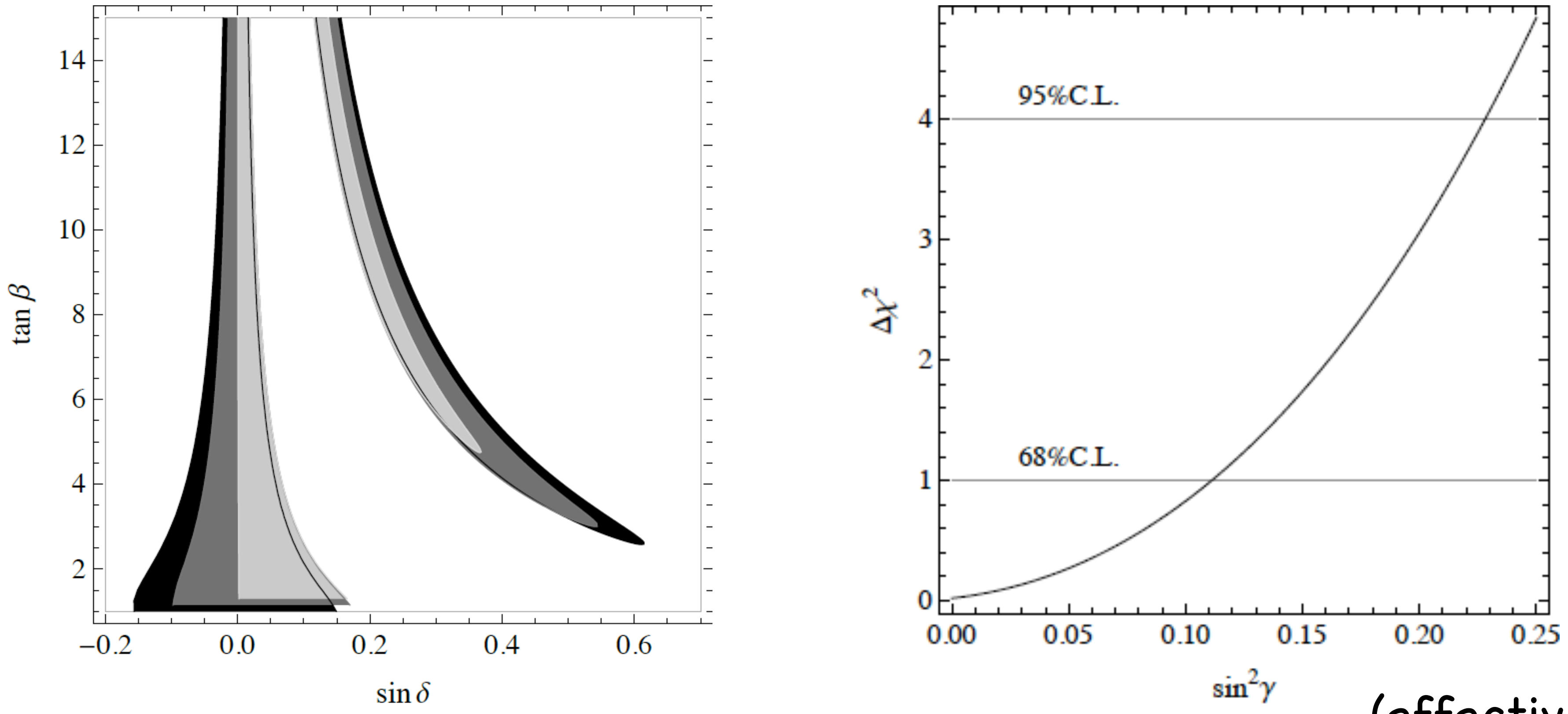
$BR(h_3 \to b\bar{b})$



(and correspondingly $\tau\bar{\tau}$ )

# A projection from the measurements of the signal strenghts (ATLAS and CMS preliminary) on the mixing angles

**Now**

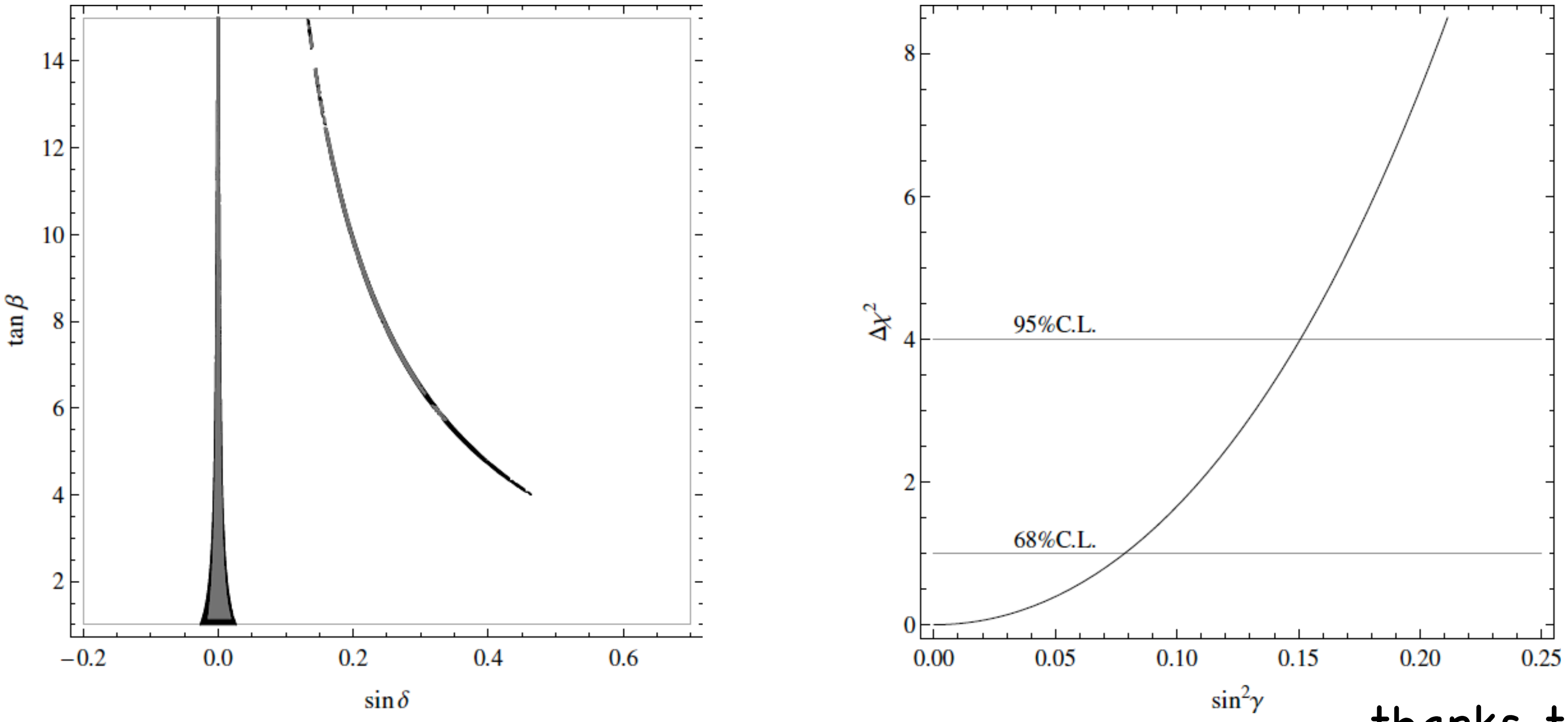


(effective $BR_{inv}$ )

**LHC14**

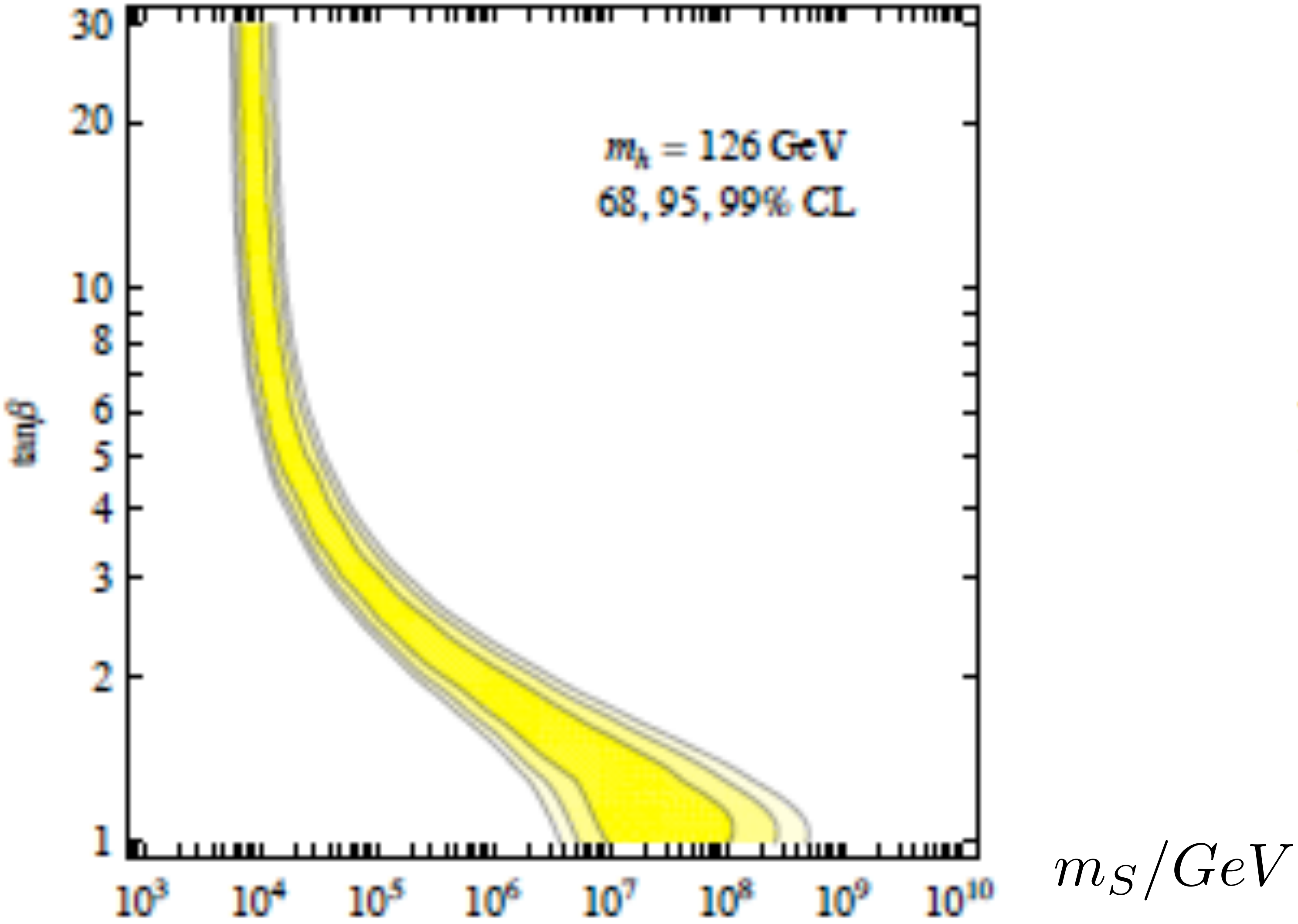
at $300 fb^{-1}$

(central values as in the SM)

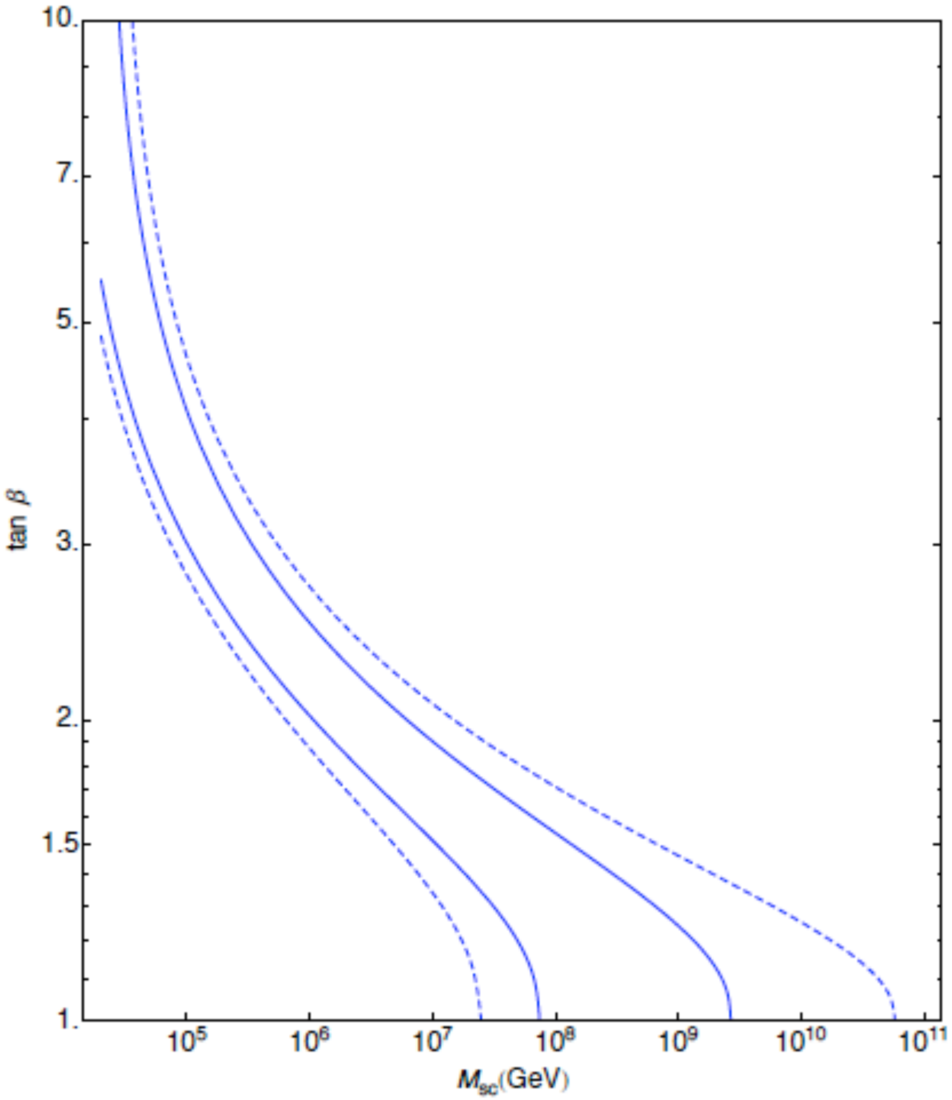


thanks to Kannike

# An alternative supersymmetric view



SUSY scalars at $m_S$
SUSY fermions at ~TeV



gauginos only at ~ TeV

Arkani-Hamed, Dimopoulos 2004
Giudice, Strumia 2011
Arkani-Hamed et al 2012

[If $m_S < T_R$, not to overclose the universe by a stable LSP, $m_S < 10 \div 100\ TeV$]

Hall et al, 2013

A less motivated (?) but simpler (?) picture

# What can we expect from (and for) flavour physics?

$$\Delta\mathcal{L} = \Sigma_i \frac{1}{\Lambda_i^2}\mathcal{O}_i$$

In some cases $\Lambda_i \gtrsim 10^3 \div 10^4 TeV$ , unless some restriction operative

Is it possible that...

$$\Delta\mathcal{L} = \Sigma_i \frac{c_i}{\Lambda_i^2}\xi_i\mathcal{O}_i$$

with $\xi_i$ controlled by symmetries or some dynamics and $c_i = O(1)$

and $\Lambda_i \approx 4\pi v \approx 3\ TeV$

- strongly interacting EWSB
- new weakly int. particle(s) at ~v

**Flavour ⇔ EWSB**

# Breaking of flavour symmetries embedded in few basic parameters

$U(3)_Q \times U(3)_u \times U(3)_d \equiv \boxed{U(3)^3}$

$Y_u = (3, \bar{3}, 1) \quad Y_d = (3, 1, \bar{3})$ (MFV)

Chivukula, Georgi 1987 (TC)
Hall, Randall 1990 (SUSY)
D'Ambrosio et al 2002 (general)

$U(2)_Q \times U(2)_u \times U(2)_d \equiv \boxed{U(2)^3}$

B, Isidori et al 2011 (general)

$Y_u, Y_d$ split under $U(2)^3$ - representations

$$Y_u = \lambda_t \begin{bmatrix} \Delta_u & V_Q \\ V_u^T & 1 \end{bmatrix} \qquad Y_d = \lambda_b \begin{bmatrix} \Delta_d & V'_Q \\ V_d^T & 1 \end{bmatrix}$$

Requiring a small breaking of $U(2)^3$ : $V = V_Q \propto V'_Q \quad ||V|| = O(V_{cb})$
and, by consistency with flavour data, $||V_u||, ||V_d|| << ||V||$

$\Big($ $U(3)^3$ at large $\tan\beta$ → $U(2)^3$ Feldmann, Mannel 2008
Kagan et al 2009 $\Big)$

# The $\Delta F = 2$ case

$U(3)^3$

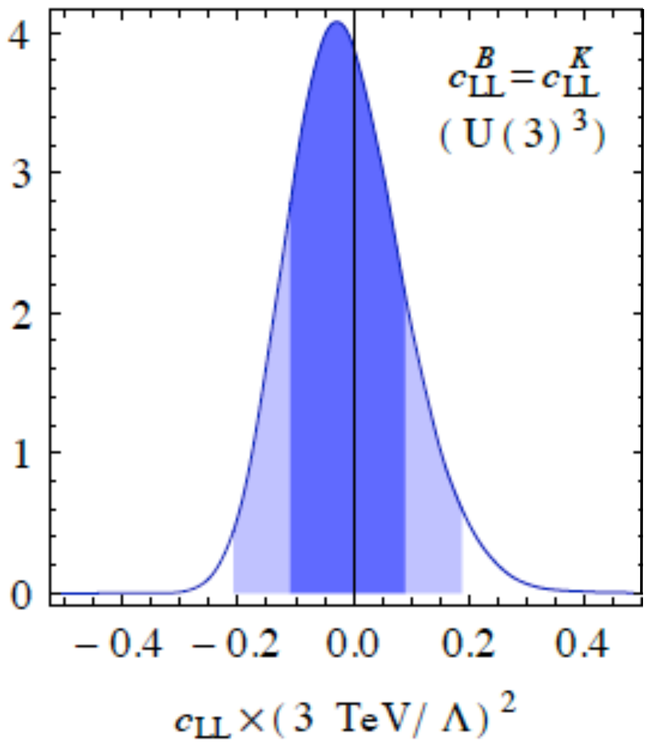
$U(2)^3$

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

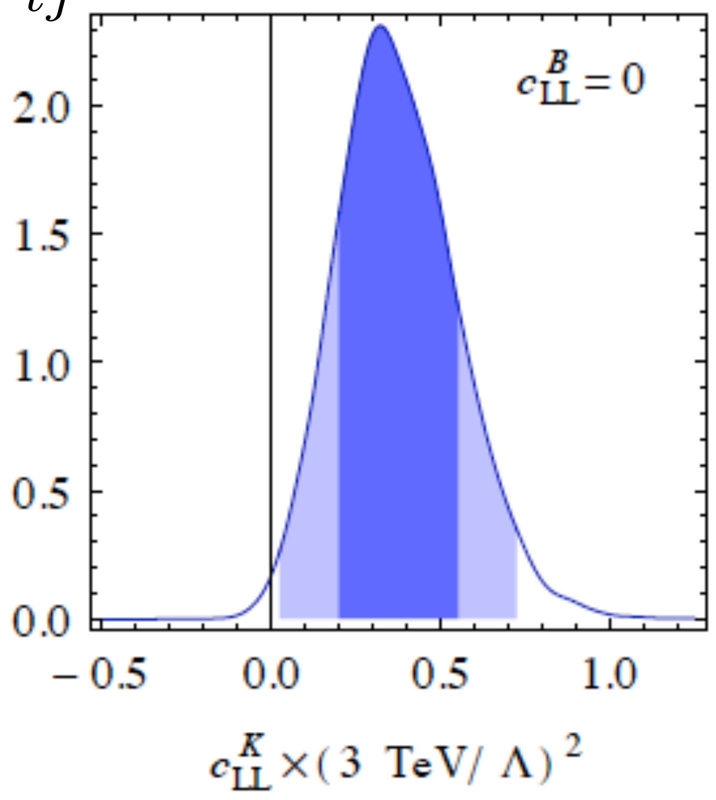
$$\xi_{ij} = V_{ti}V_{tj}^*$$

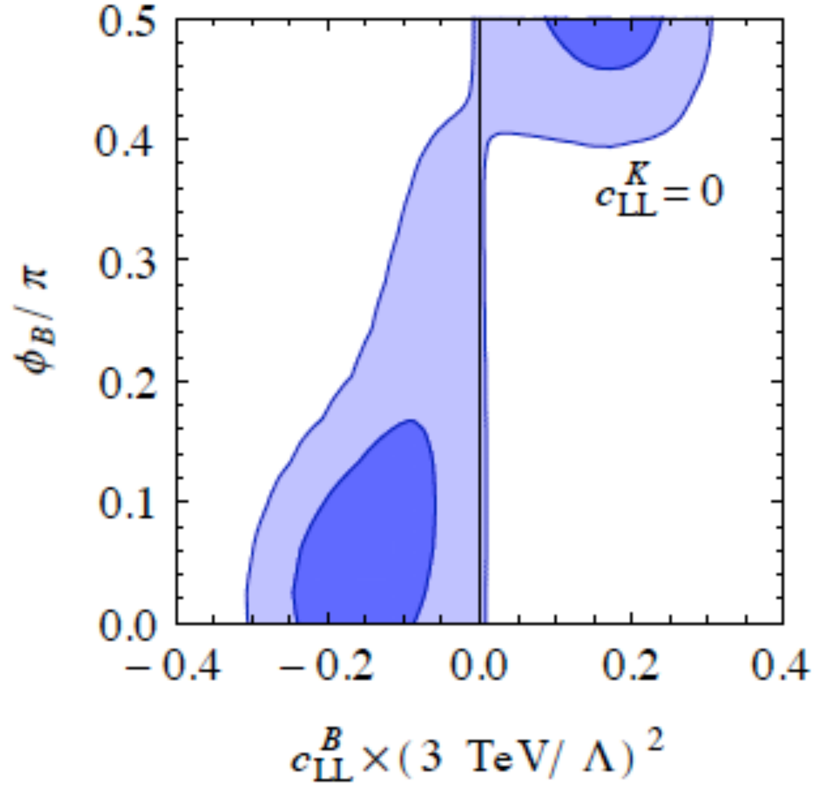
$$\frac{c_{LL}^K}{\Lambda^2}\xi_{ds}^2\frac{1}{2}(\bar{d}_L\gamma_\mu s_L)^2$$

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



(cannot fit the "discrepancy")





B, Buttazzo et al 2012

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

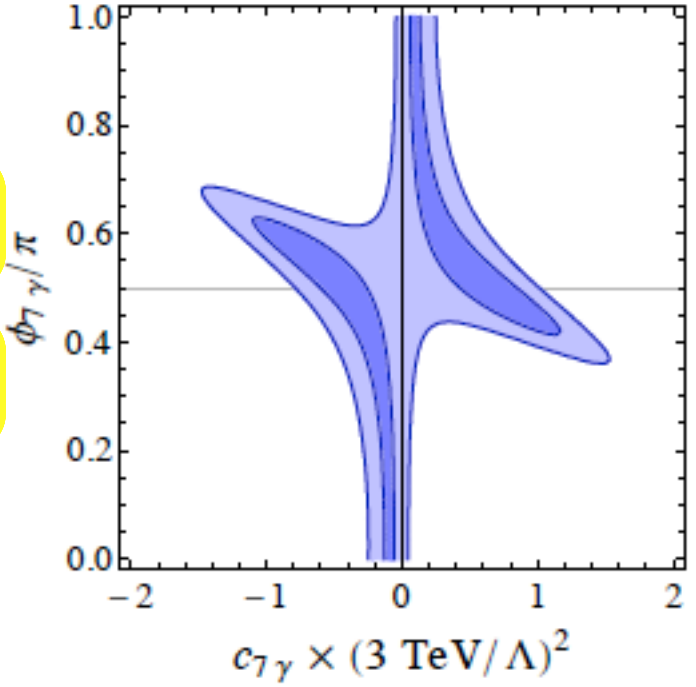
**Chirality breaking**
**(cromo-)magnetic operators**

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

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

$U(3)^3$

$U(2)^3$



**Chirality conserving op.s**

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

$B \rightarrow K(\pi)\mu\mu$ }

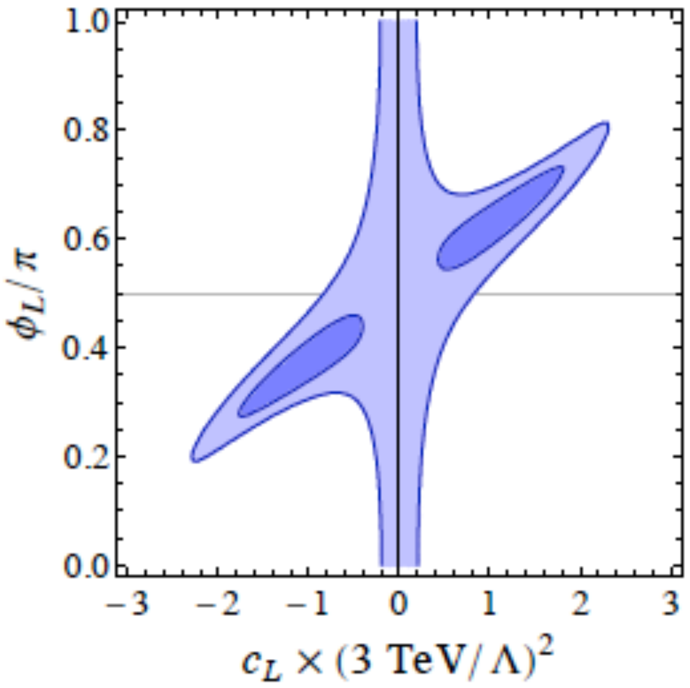
$B_s \rightarrow \mu\mu$

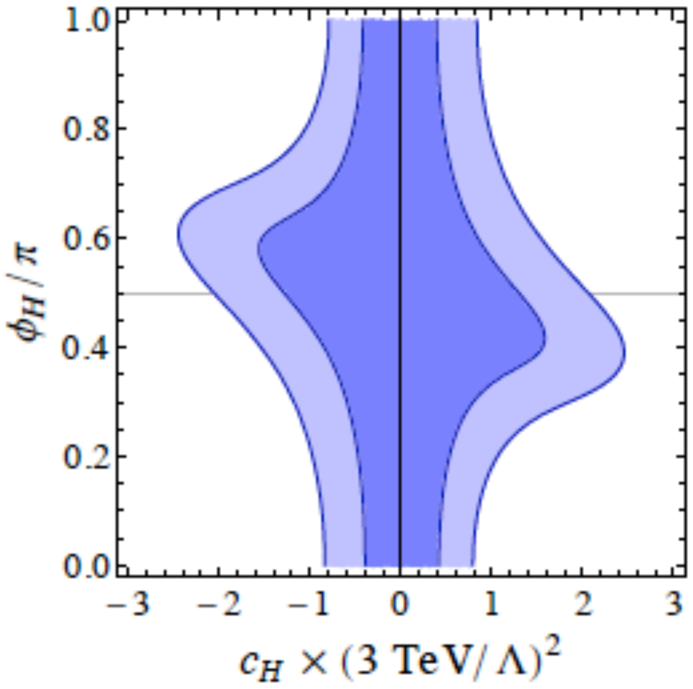
$[K \rightarrow \pi\nu\nu]$

correlated

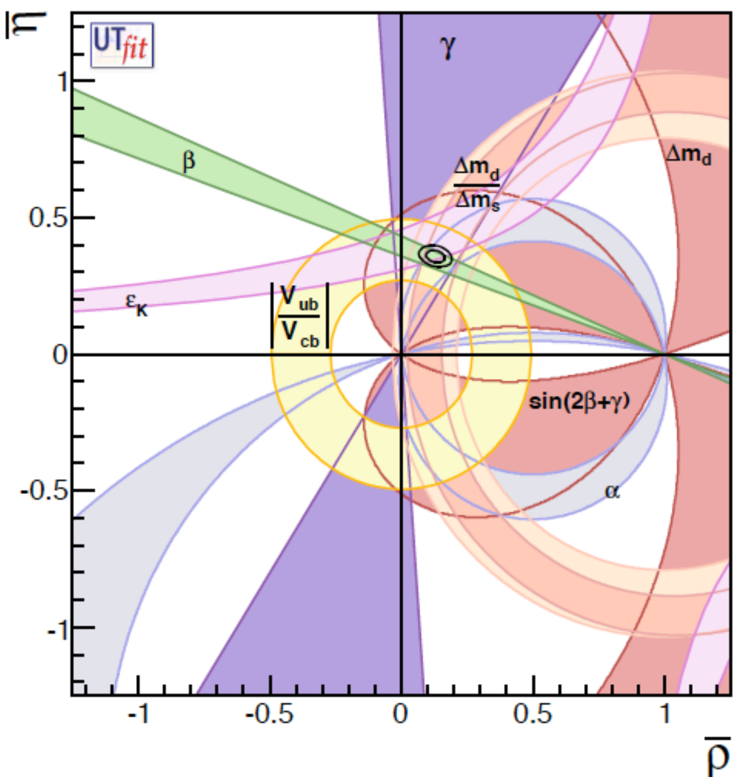
no phase in $U(3)^3$

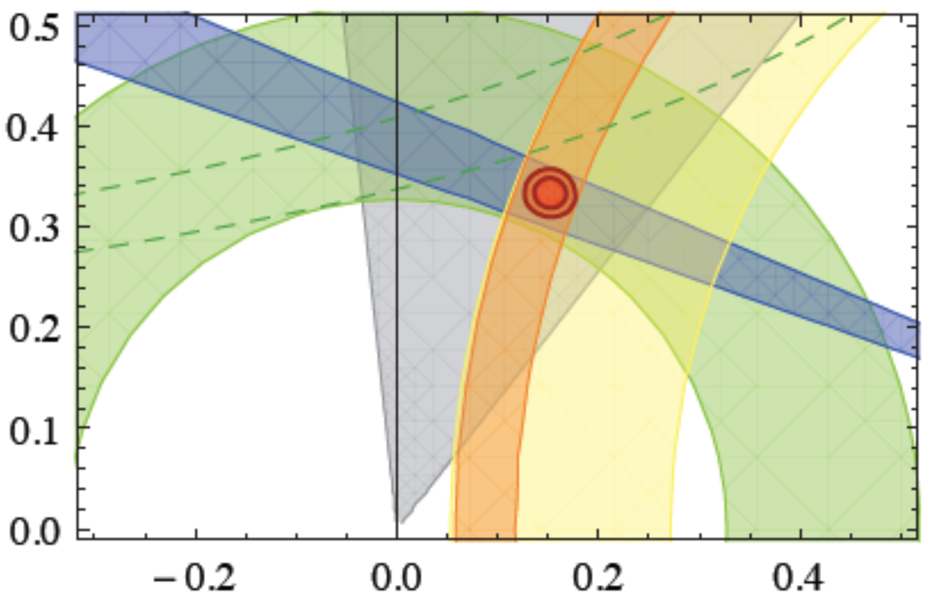
$U(2)^3$

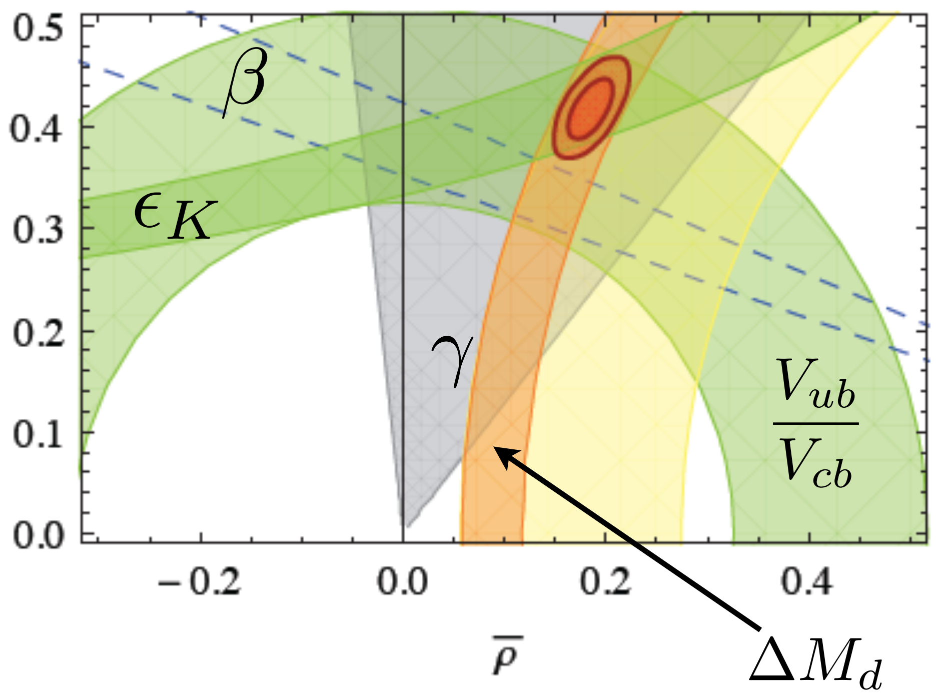




# $\Delta F = 2$ key measurements







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

**$U(2)^3$**

$$\epsilon_K = \epsilon_K^{\rm SM(tt)}\left(1+h_K\right) + \epsilon_K^{\rm SM(tc+cc)},$$

$$S_{\psi K_S} = \sin\left(2\beta + \arg\left(1+h_B e^{i\phi_B}\right)\right),$$

$$S_{\psi\phi} = \sin\left(2|\beta_s| - \arg\left(1+h_B e^{i\phi_B}\right)\right)$$

$$\Delta M_d = \Delta M_d^{\rm SM}\left|1+h_B e^{i\phi_B}\right|,$$

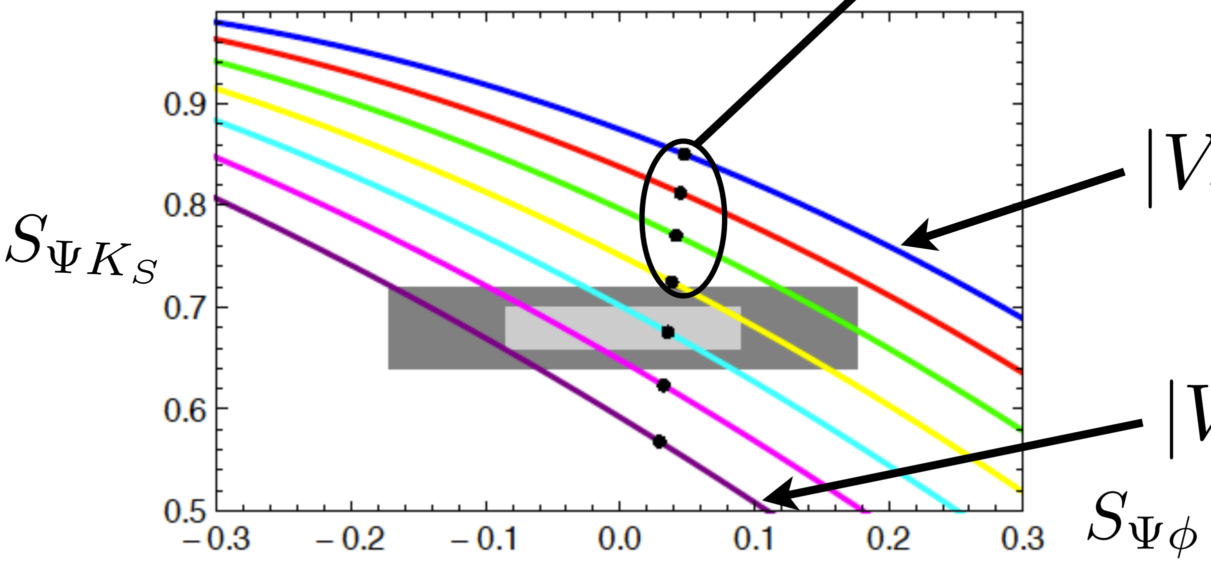
$$\frac{\Delta M_d}{\Delta M_s} = \frac{\Delta M_d}{\Delta M_s}\Big|_{SM} = 34.5 \pm 3.0$$

$$\frac{\Delta M_d}{\Delta M_s}\Big|_{exp} = 35.0 \pm 0.3$$

$$\Rightarrow \boxed{\gamma \approx 70^0}$$

SM centered on $\epsilon_K$

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



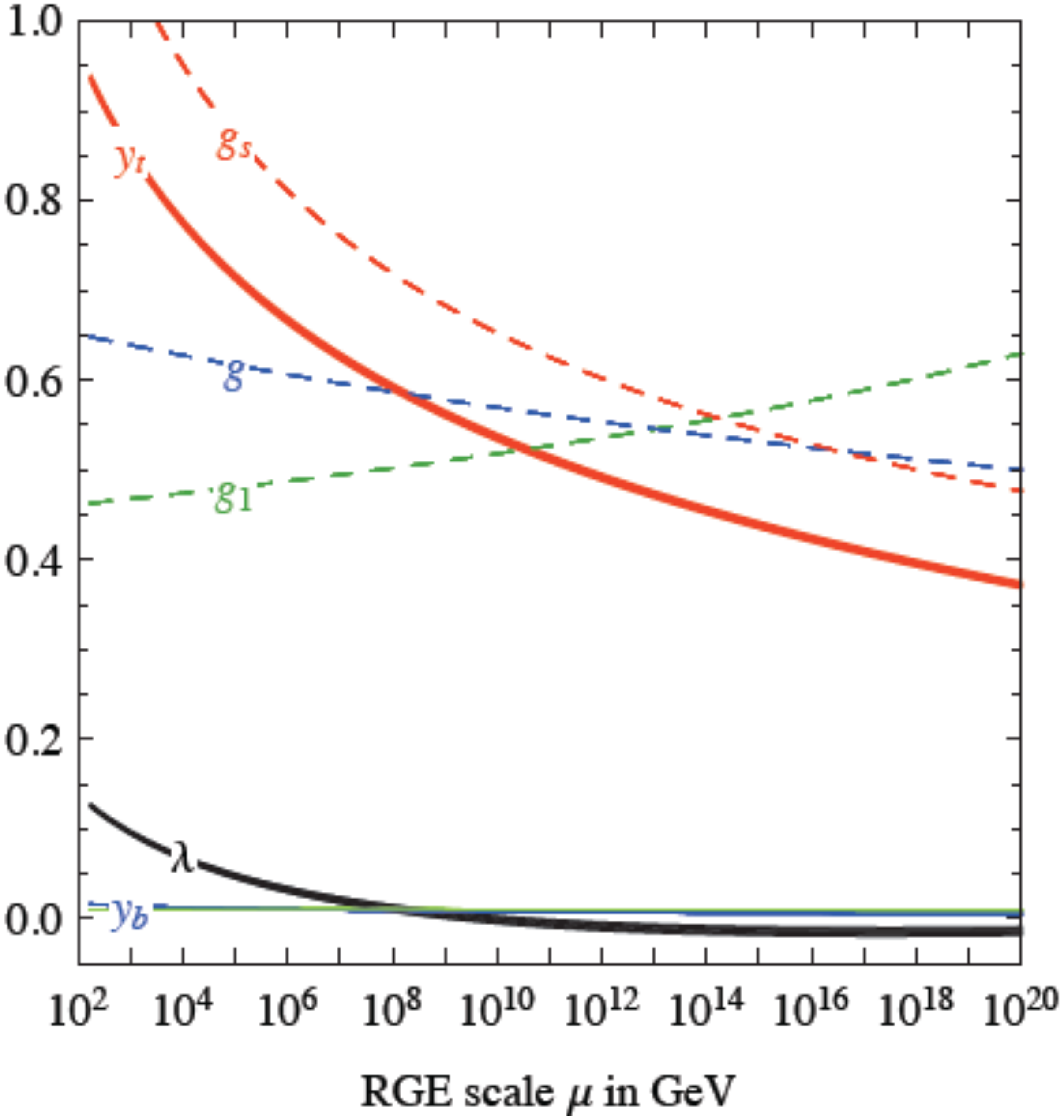
$|V_{ub}| = 0.0046$

$|V_{ub}| = 0.0028$

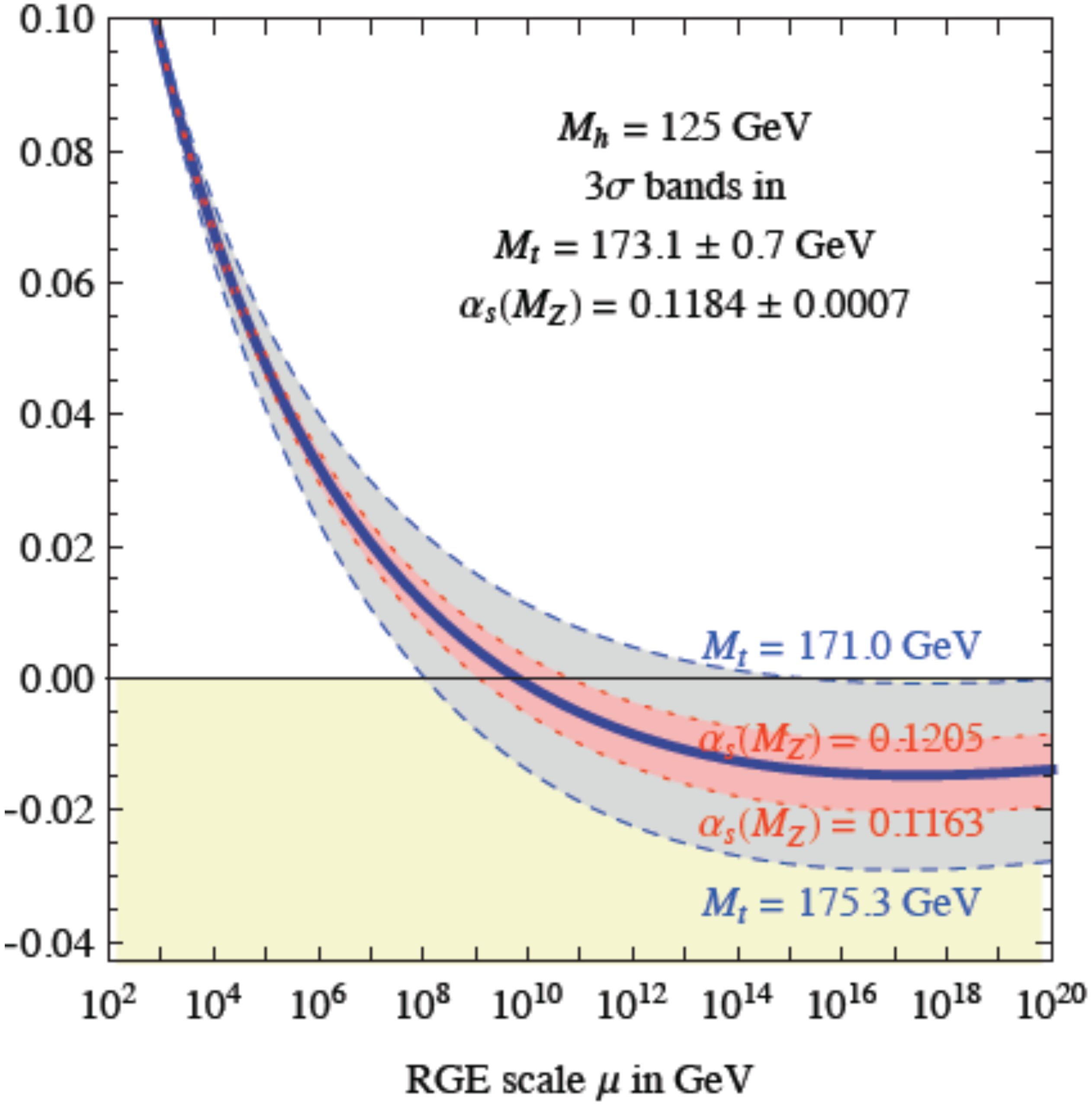
Buras, Girbach 2012

# What if the Higgs boson likes to be unnatural and the SM is unchanged up to very high energies?

largest couplings



Higgs self-coupling

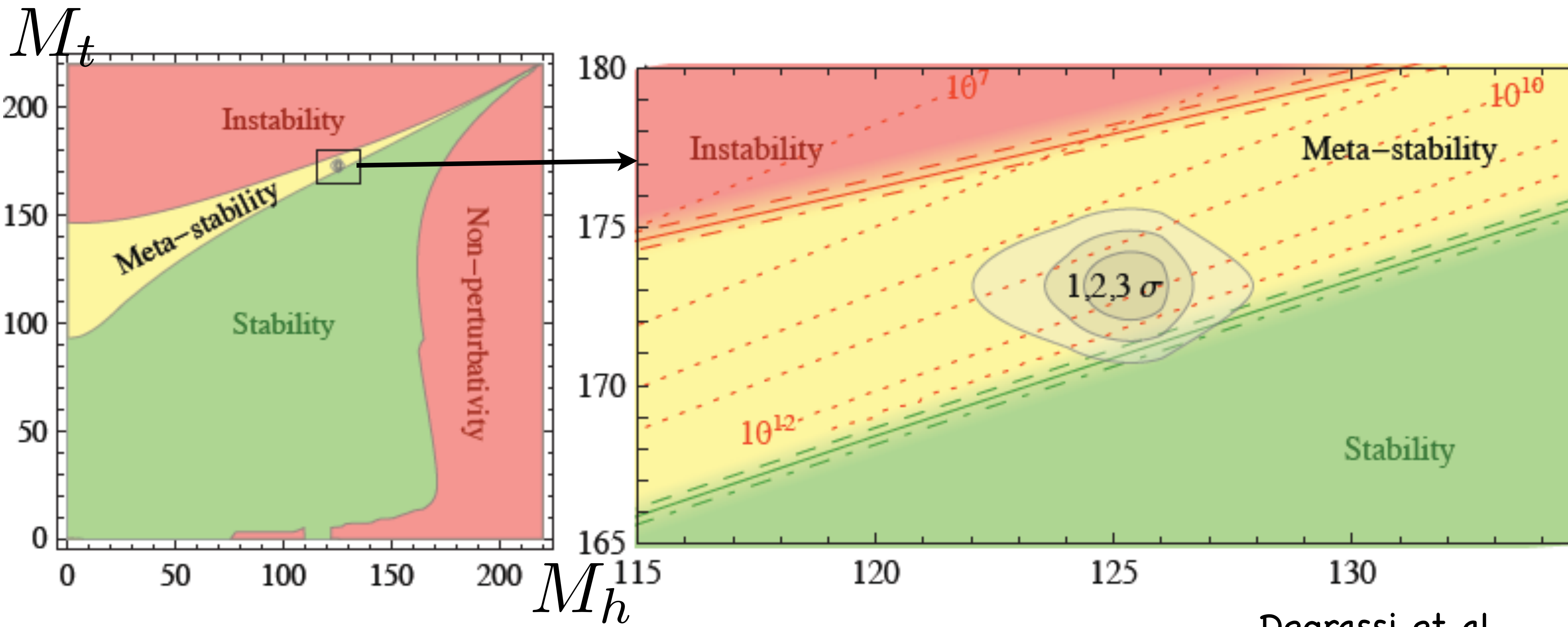


Degrassi et al 2012
Chetyrkin, Zoller 2005
Bezrukov et al 2005

# A special meaning for λ≈0 at MPl?

Nielsen et al 1988
Shaposhnikov et al 2009

Assume SM unchanged up to $M_{Pl}$

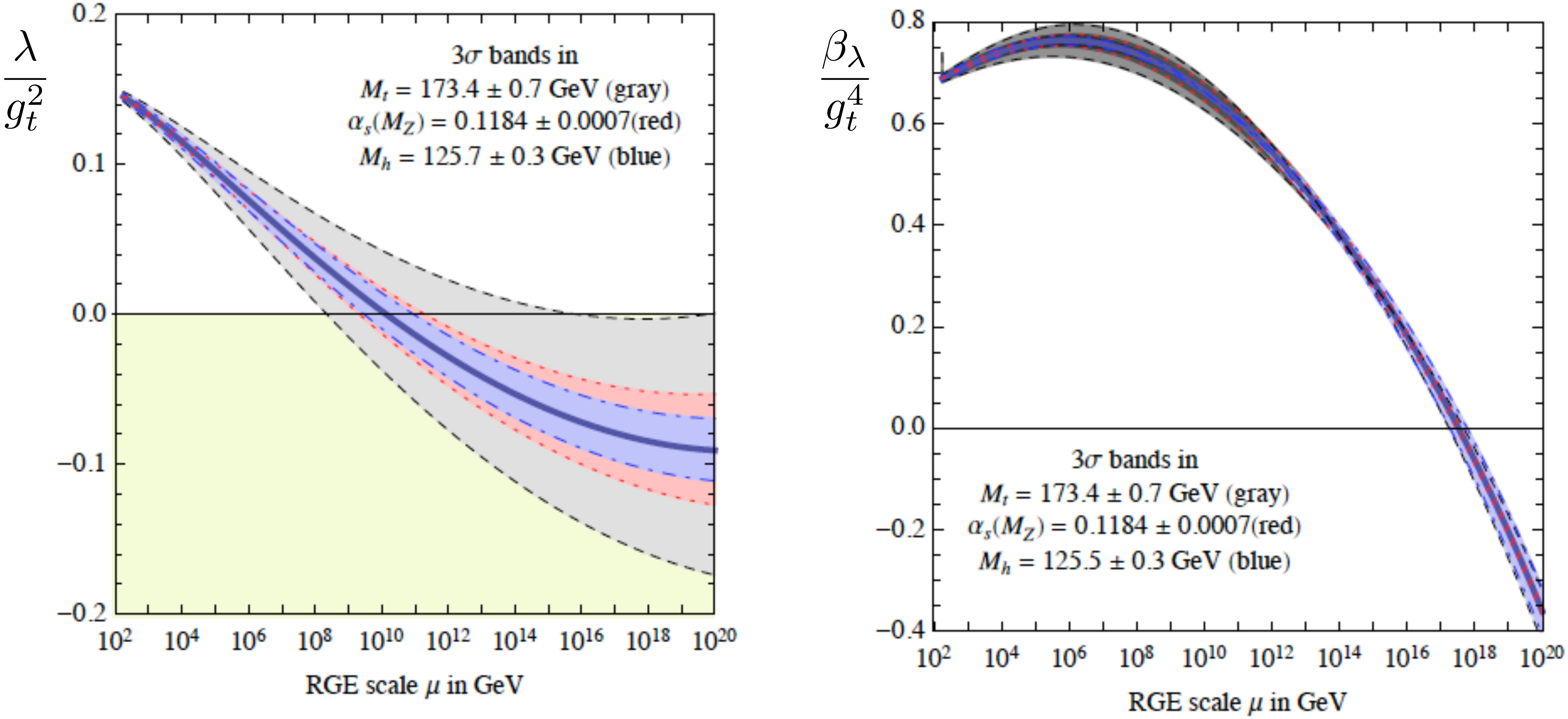


Degrassi et al

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 (anthropic pressure, ...)

# What's the real evidence for $\lambda(M_{Pl}) \approx \beta_\lambda(M_{Pl}) = 0$?



Even if this improved ($g_t$, etc) how shall we know that it is not a coincidence?

Thanks to Rattazzi and Strumia