Un bosone di Higgs compatibile col Modello Standard e poi il resto di niente: cosa significa?

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Effective Quantum Field Theory ideology

no ideology, no expectations

- ✦ gauge symmetry
- ✦ field content
- ✦ local effective lagrangian

- ✳ renormalizability
- ✳ global symmetries

needn't be fundamental
but just accidental
low energy features

Il Modello Standard come teoria efficace

con scala fundamentale $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

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d=4

$$+ \quad \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \quad \frac{c_{ijkl}}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \ldots$$

$$+ \quad \ldots$$

d>4

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d>4

$\Lambda_{UV} \gg$ TeV (pointlike limit) nicely accounts for ‘what we see’

$$+\,\theta\,\tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu}$$

d=4

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$$+\, c\Lambda_{UV}^2\, H^\dagger H$$ d=2

$$+\,\theta\, \tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu}$$ d=4

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$$+ \quad \ldots$$

d>4

$\Lambda_{UV} \gg$ TeV (pointlike limit) nicely accounts for 'what we see' i tre problemi

$$+\Lambda^4_{UV}\sqrt{g}$$ d=0

$$+c\Lambda^2_{UV}\,H^\dagger H$$ d=2

$$+\theta\,\tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu}$$ d=4

$$\mathcal{L}_{SM} \;=\; \mathcal{L}_{kin} + gA_\mu\bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$ d=4

$$+ \quad \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

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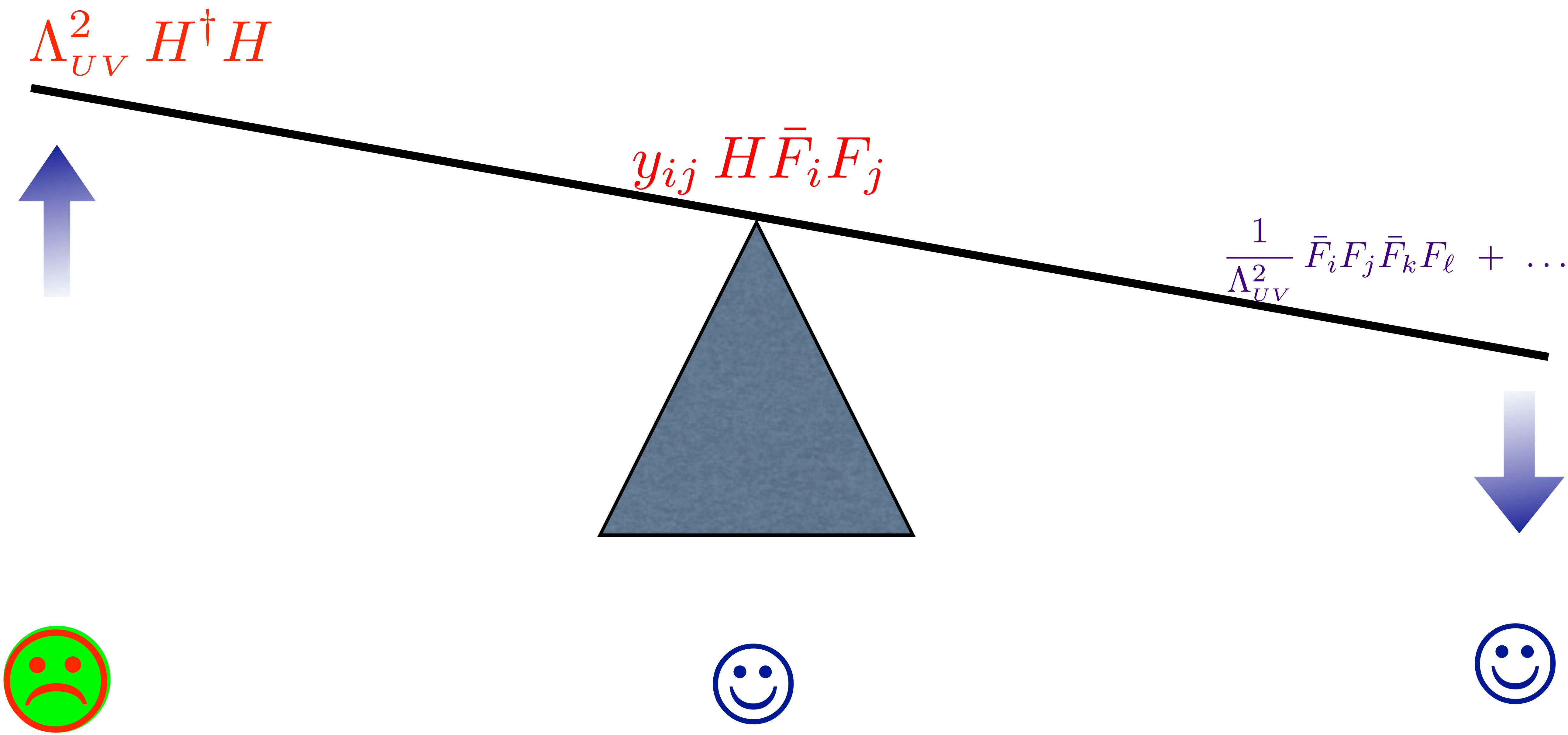
$$+ \quad \ldots$$

d>4

$\Lambda_{UV} \gg$ TeV (pointlike limit) nicely accounts for ‘what we see’

Hierarchy see-saw

Standard Model up to some $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$



Hierarchy see-saw

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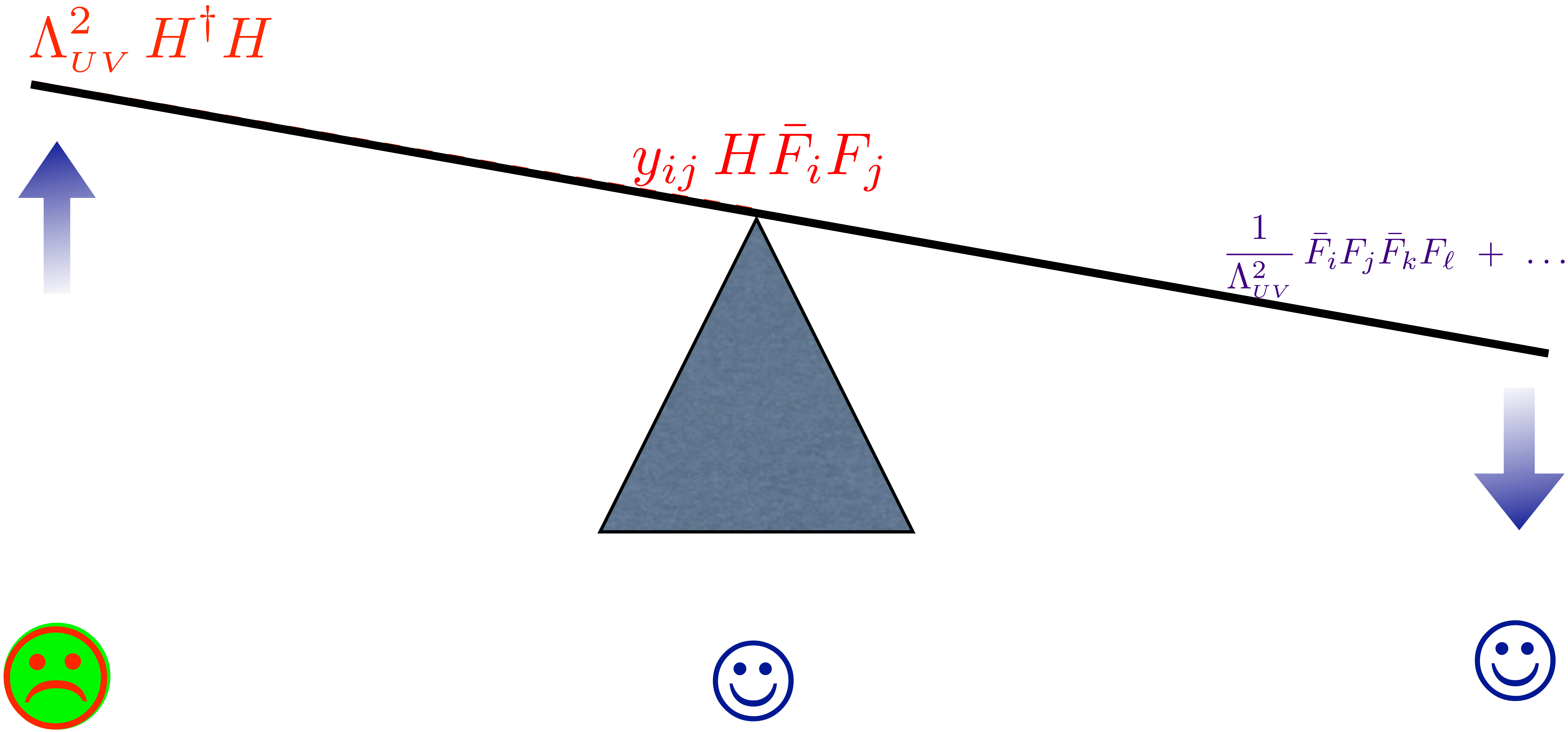

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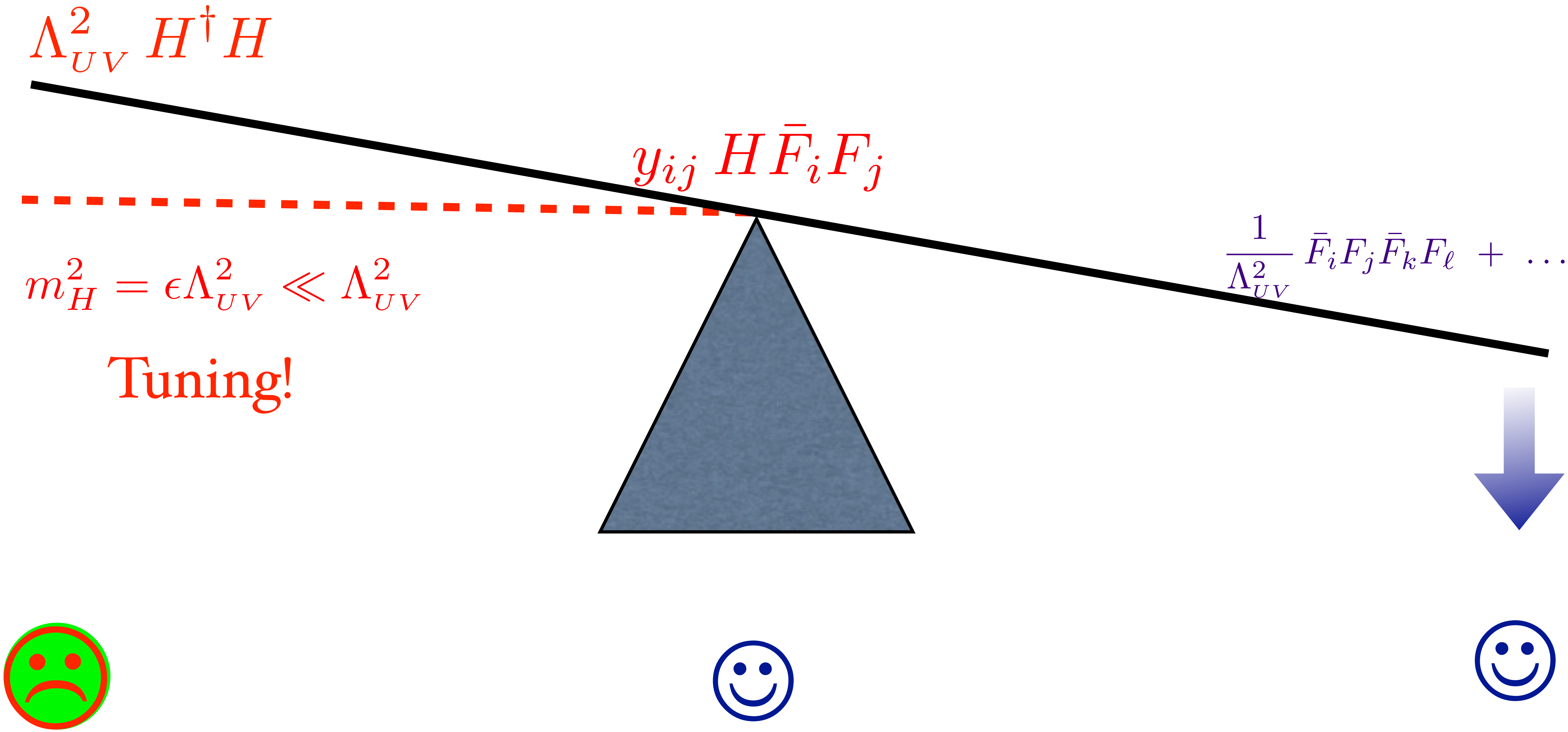
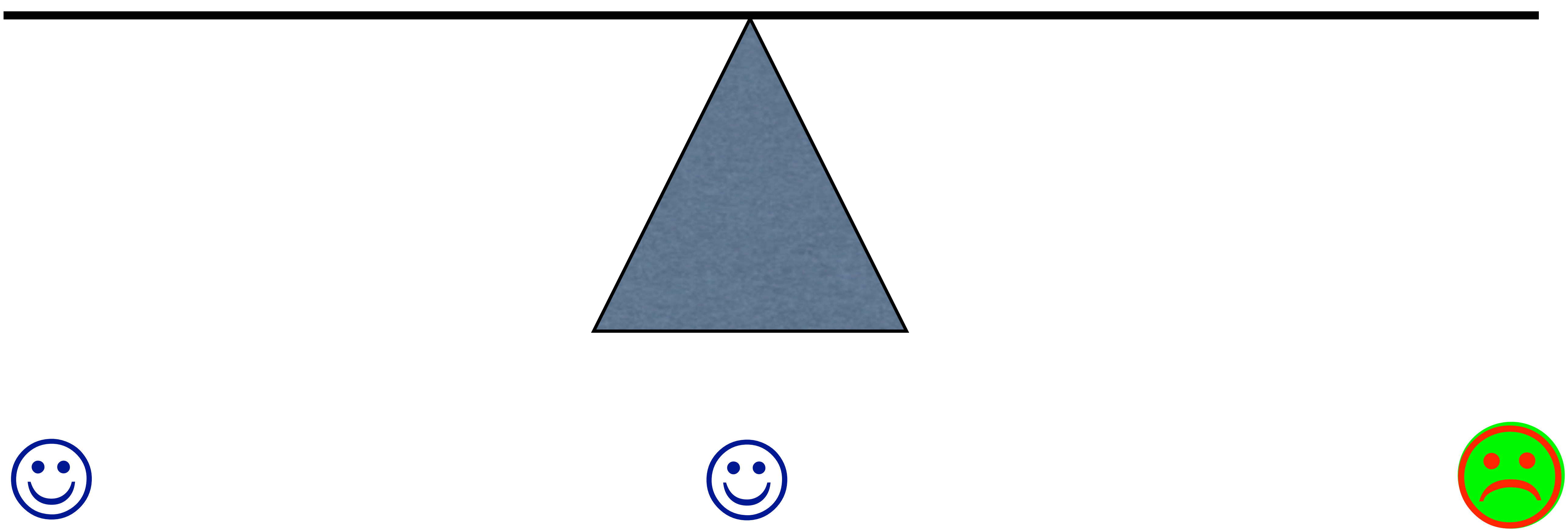


Natural SM : $\Lambda_{UV}^2 \lesssim 1\,\text{TeV}$

$\Lambda_{UV}^2\, H^\dagger H$ $\quad\quad$ $y_{ij}\, H\, \bar{F}_i F_j$ $\quad\quad$ $\frac{1}{\Lambda_{UV}^2}\, \bar{F}_i F_j \bar{F}_k F_\ell \;+\; \ldots$



The two possible microphysics scenarios

I. The SM is the correct description up to $\Lambda_{UV} \gg TeV$

- B, L and Flavor: beautifully in accord with observation
- Hierarchy remains a mystery, probably hinting that the question was not correctly posed
  - anthropic principle
  - failure of effective field theory (UV/IR connection)

II. The SM is not the correct description already at $\Lambda_{UV} \sim 1\,\mathrm{TeV}$

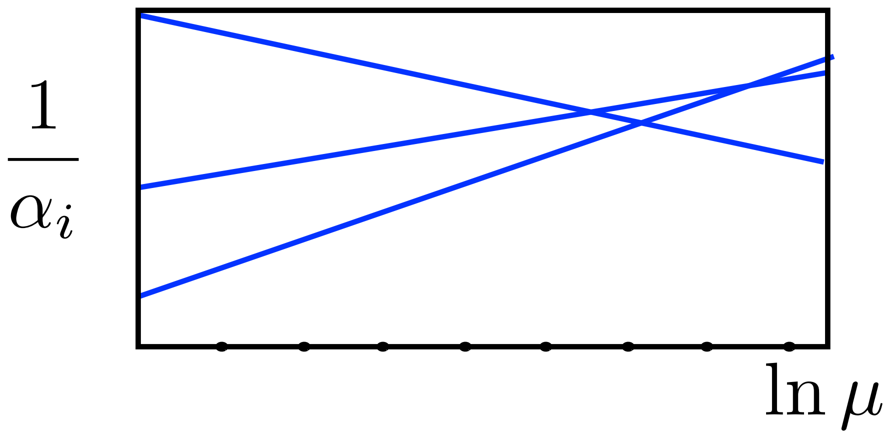
- In the correct theory the hierarchy problem does not even arise (naturalness)
- What about B, L and Flavor? in all models not nearly as nice as in SM

A high scale scenario

- $\mathcal{L}^{d=4}$ experimental success (some 2- 3-σ glitches here and there)

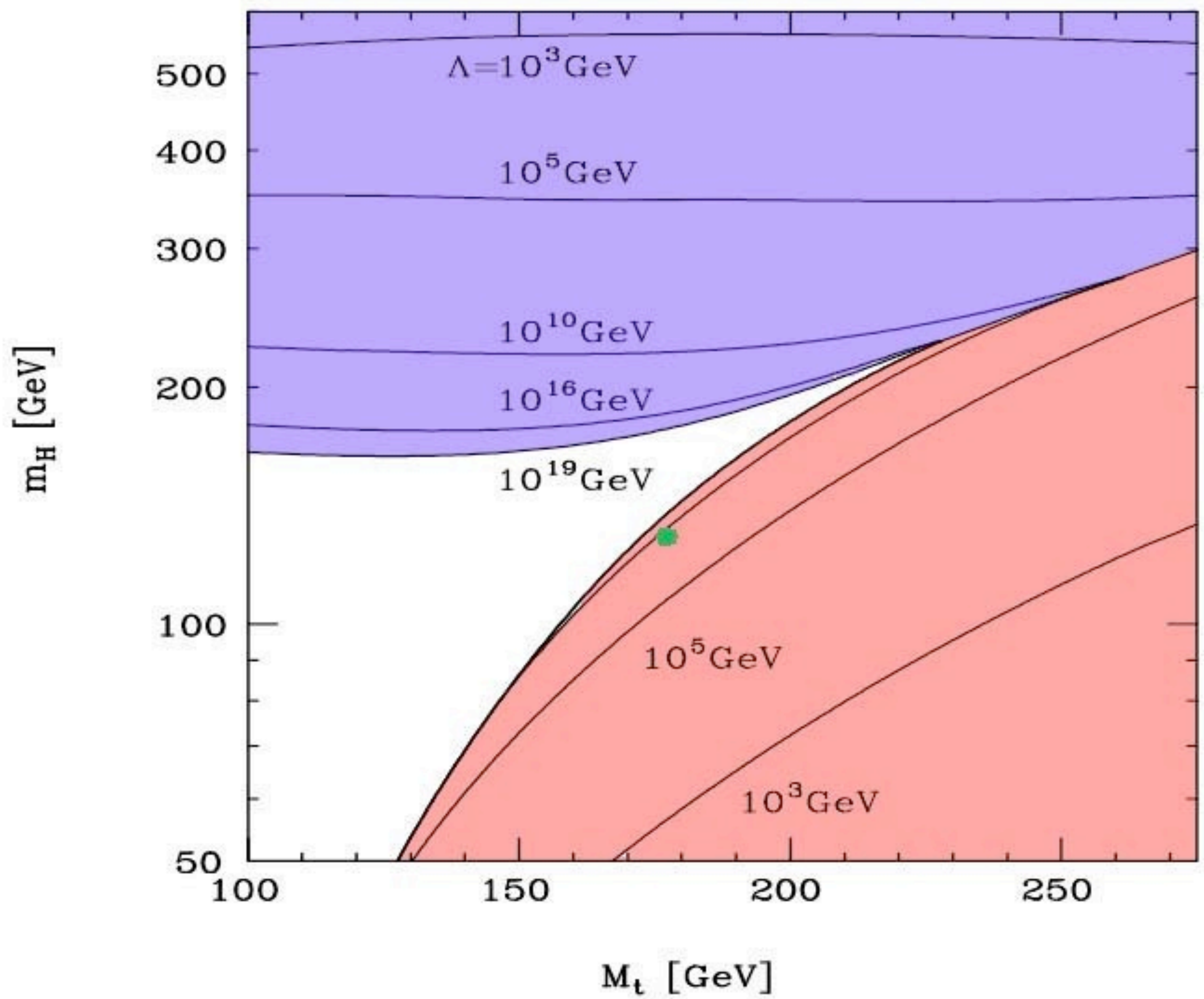
- Θ-QCD and Dark Matter ➔ high scale axion $f_a \sim 10^{12}$ GeV

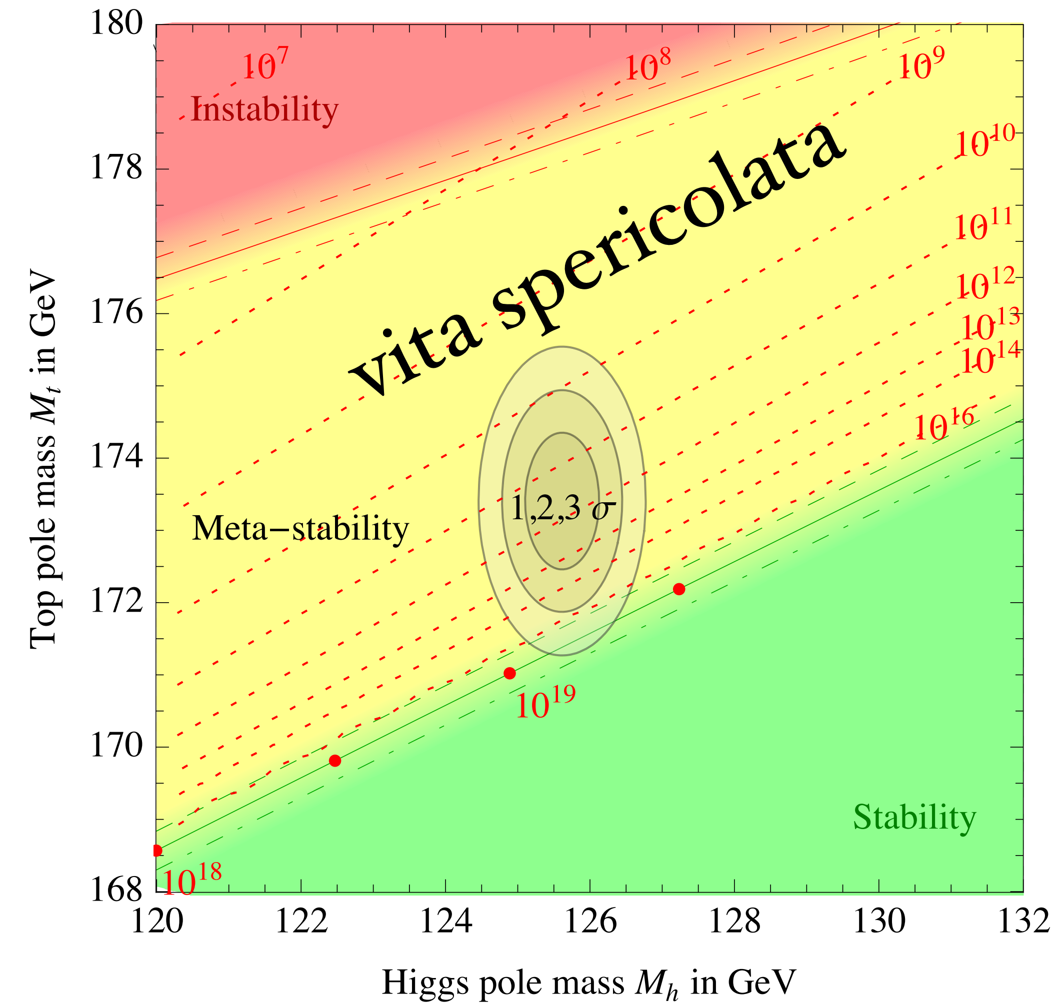
- gauge couplings ready to unify around $10^{15} \lesssim M \lesssim M_{Planck}$



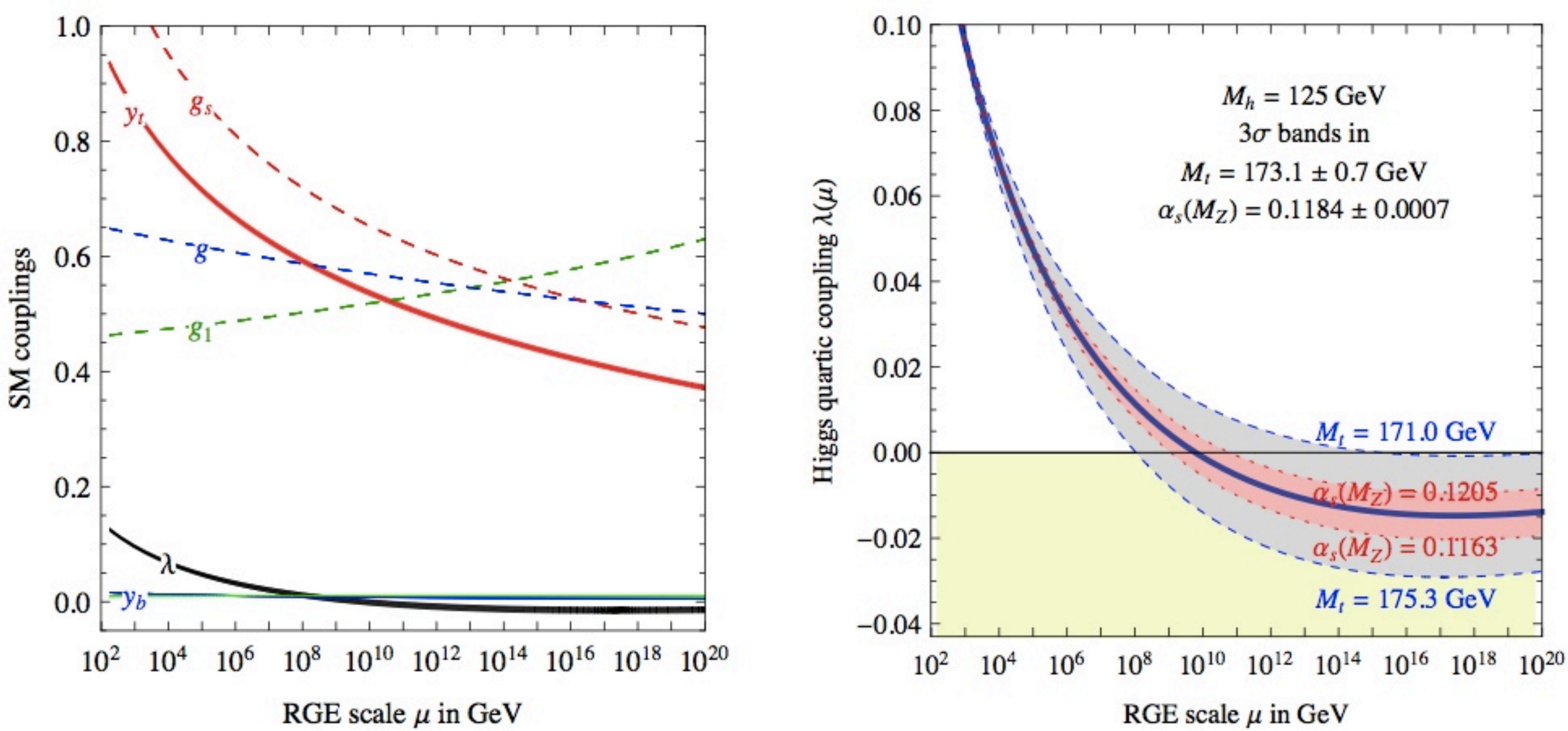
- neutrino masses $\frac{\ell\ell HH}{\Lambda}$ ➔ $m_\nu \sim \frac{v^2}{\Lambda}$ $\Lambda \sim 10^{14}$ GeV

- RG-evolution of SM couplings, including λ_h remarkably do not require lower scales

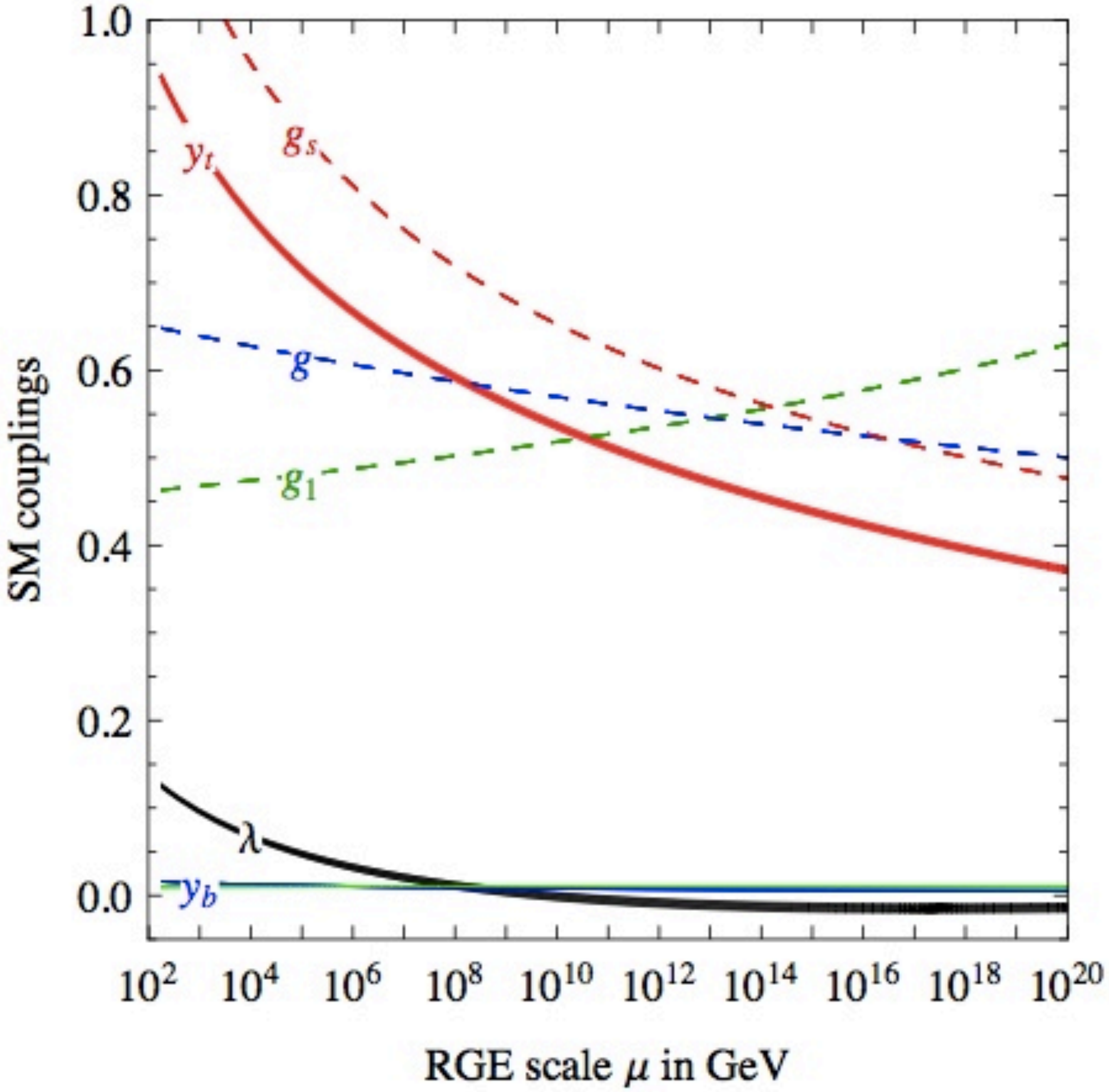


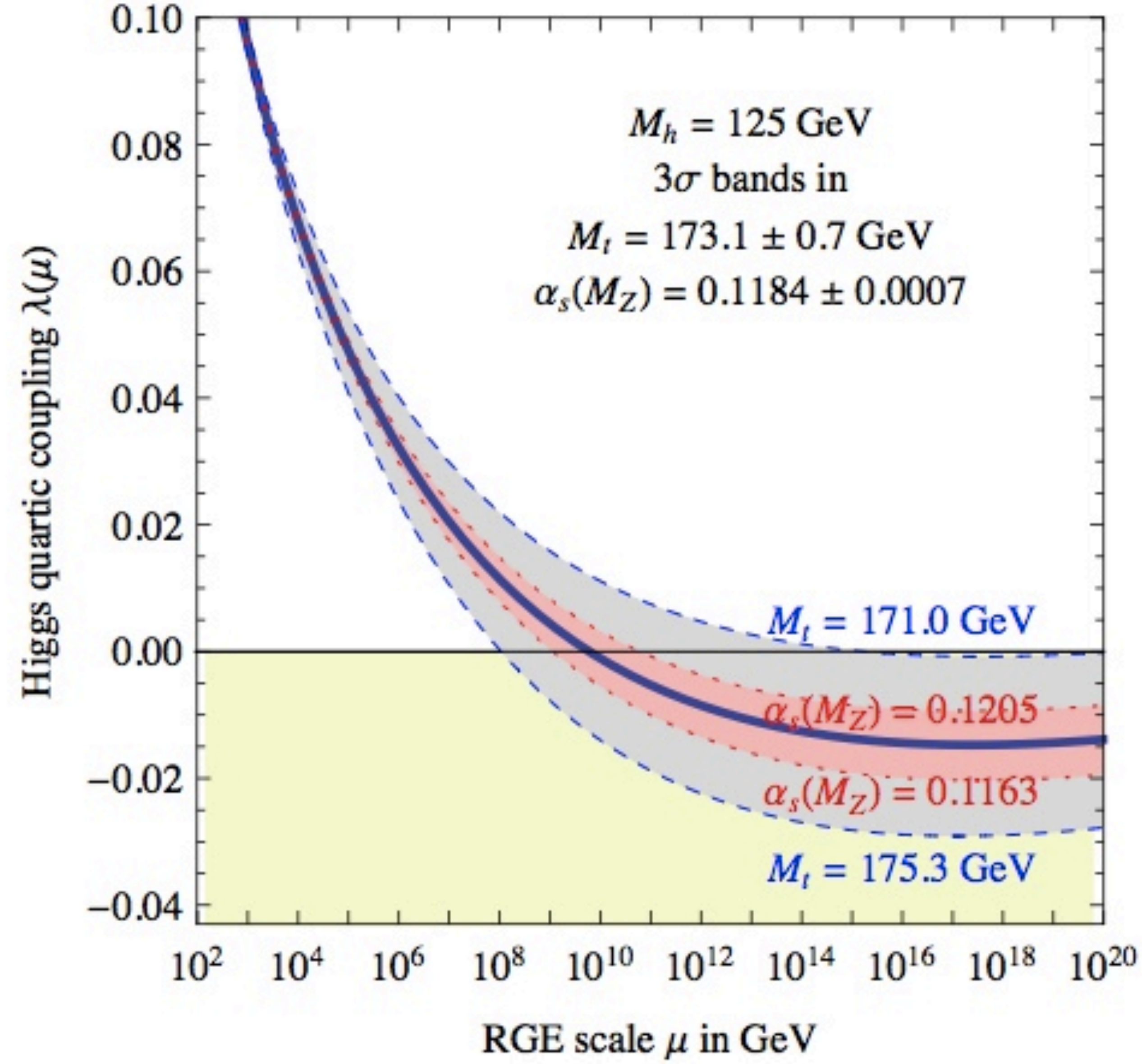


the fact that the SM lives dangerously perhaps points to
an anthropic selection of parameters
though it is hard to tell

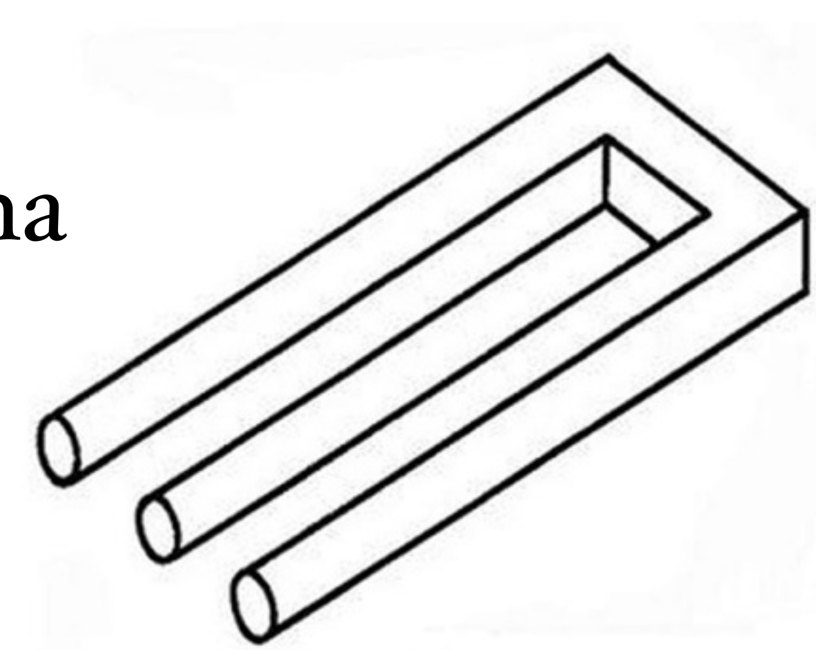


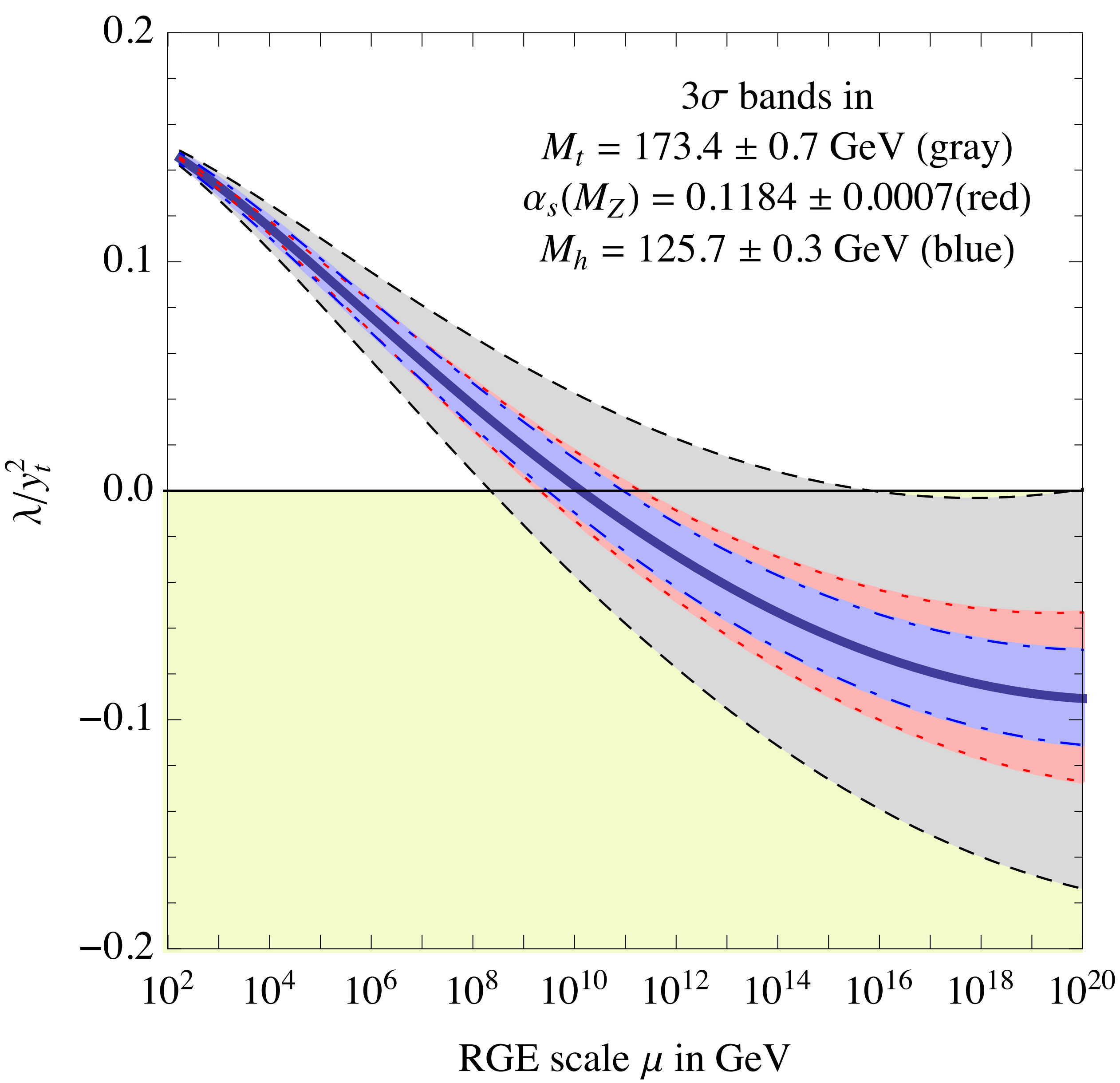
SM couplings
RGE scale μ in GeV
y_t
g_s
g
g_1
λ
y_b
1.0
0.8
0.6
0.4
0.2
0.0
10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}
Higgs quartic coupling $\lambda(\mu)$
$M_h = 125$ GeV
3σ bands in
$M_t = 173.1 \pm 0.7$ GeV
$\alpha_s(M_Z) = 0.1184 \pm 0.0007$
$M_t = 171.0$ GeV
$\alpha_s(M_Z) = 0.1205$
$\alpha_s(M_Z) = 0.1163$
$M_t = 175.3$ GeV
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04





ma l’occhio a volte inganna





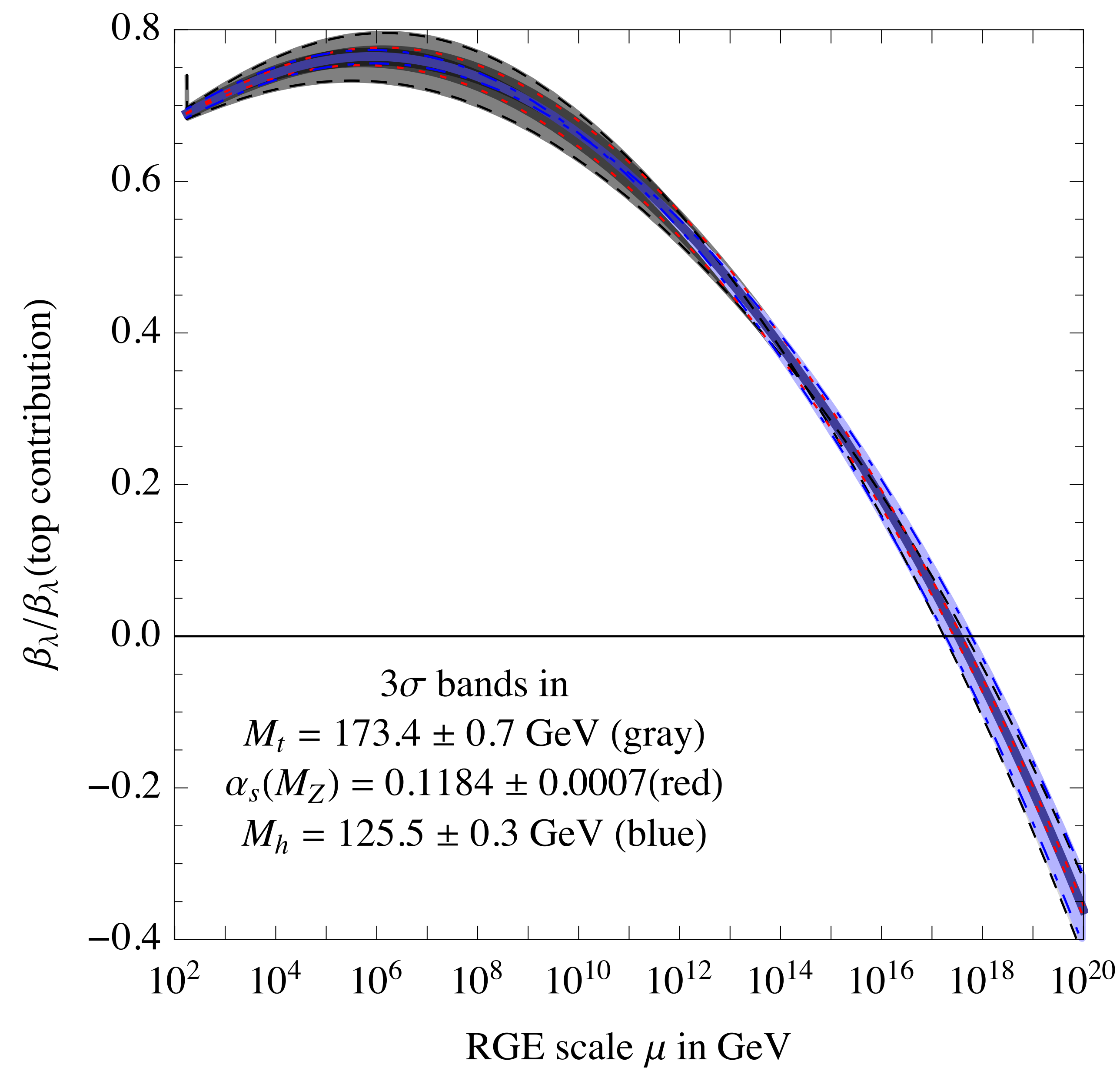


Figure 1:
per Rattazzattila

Lower: *Figure*

Grazie Strumia!

The two natural scenarios for electroweak symmetry breaking

Elementary Higgs exists
but a symmetry
protects its mass

Supersymmetric Models

No elementary Higgs
exists

Technicolor,
Composite Light Higgs
(and its holograms)

Large Extra Dimensions: exciting, fantastic, great, but not very plausible

plus a list of not even wrong scenarios, ex. UED

Flavor ?

Supersymmetry: the existence of scalar matter fields introduces a myriad of $d \leq 4$ terms violating F, B and L

$$\mathcal{L}^{d\leq 4} = m^2_{ij}\tilde{Q}^\dagger_i\tilde{Q}_j + A_{ij}Y^D_{ij}\tilde{Q}_i\tilde{D}_jH_d + \lambda_{ijk}\tilde{U}_iD_jD_k + \ldots$$

Naive Composite Higgs (TC) : the Yukawa themselves are $d > 4$

$$Y_{ij}\, H\, \bar{Q}^i_L Q^j_R \;\rightarrow\; Y_{ij}\,\frac{1}{\Lambda_F^2}\,(\bar{\Psi}\Psi)Q^i_L Q^j_R \qquad\qquad m_{ij} = Y_{ij}\,\frac{v_F^3}{\Lambda_F^2}$$

Λ_F must be not too far above weak scale: expect unwanted FCNC

In all natural models, extra assumptions (often clever) are needed to meet flavor physics constraints

Approaches

Symmetry

pick a subgroup of $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$

pick a set of spurions to break it

construct a lagrangian using the selection rules

Dynamics

mass mixing hierarchy from radiative corrections

flavor from geography in extra-dim

flavor from partial compositeness

↕ holography

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Dynamics

mass mixing hierarchy from radiative corrections
flavor from geography in extra-dim ↕ holography
flavor from partial compositeness

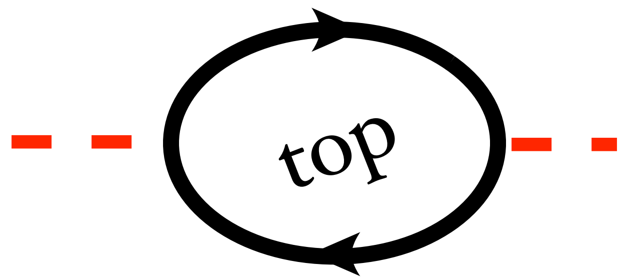
unfortunately disfavored in natural theories

What naturalness demands

supersoft models: Higgs mass parameter fully saturated by IR physics

- dirac gauginos in supersymmetry
- general composite Higgs

$\delta m_H^2 =$



$\sim \dfrac{3\lambda_t^2}{8\pi^2} M^2$

$m_h = 125\,\text{GeV}$

tuning

$\left(\dfrac{400\,\text{GeV}}{M}\right)^2$

soft models: Higgs mass logarithmically sensitive to UV

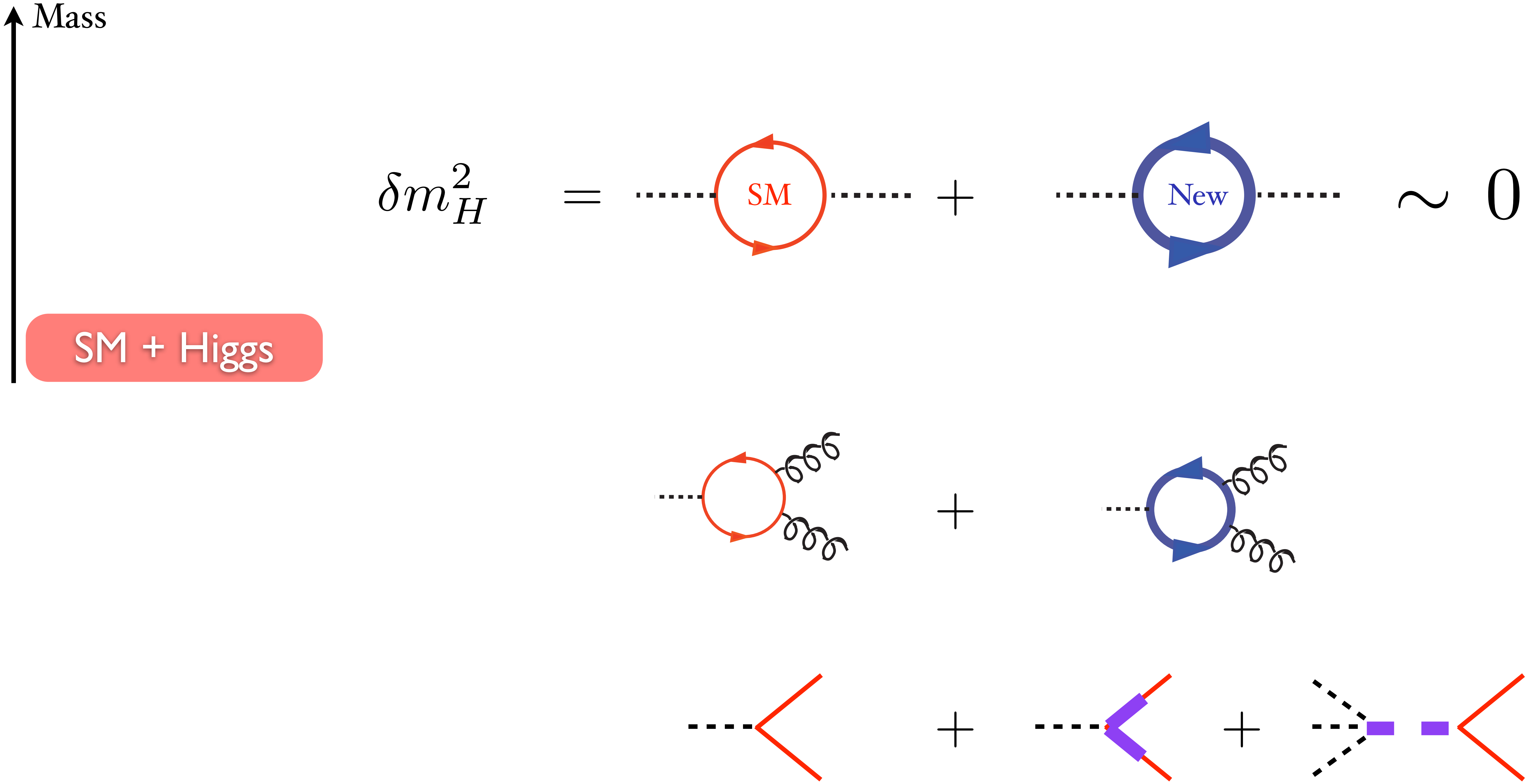
- MSSM and its extensions with high scale mediation

$m_h^2 \sim m_Z^2 \sim m_{\tilde{t}}^2$

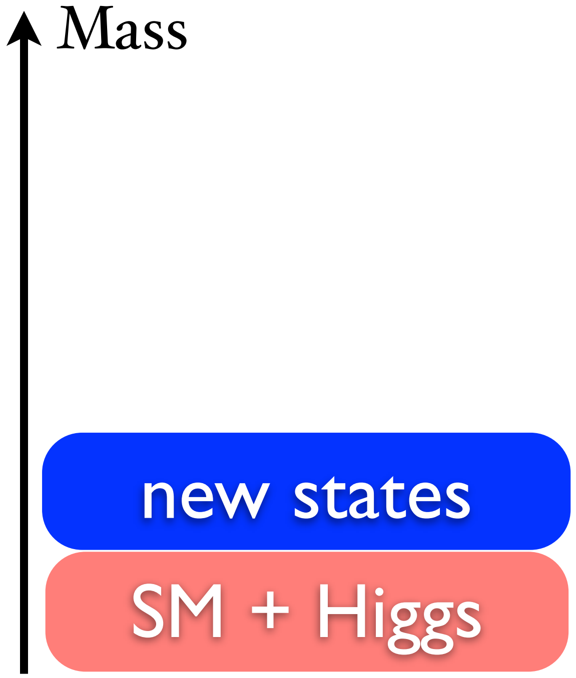
$m_h = 125\,\text{GeV}$

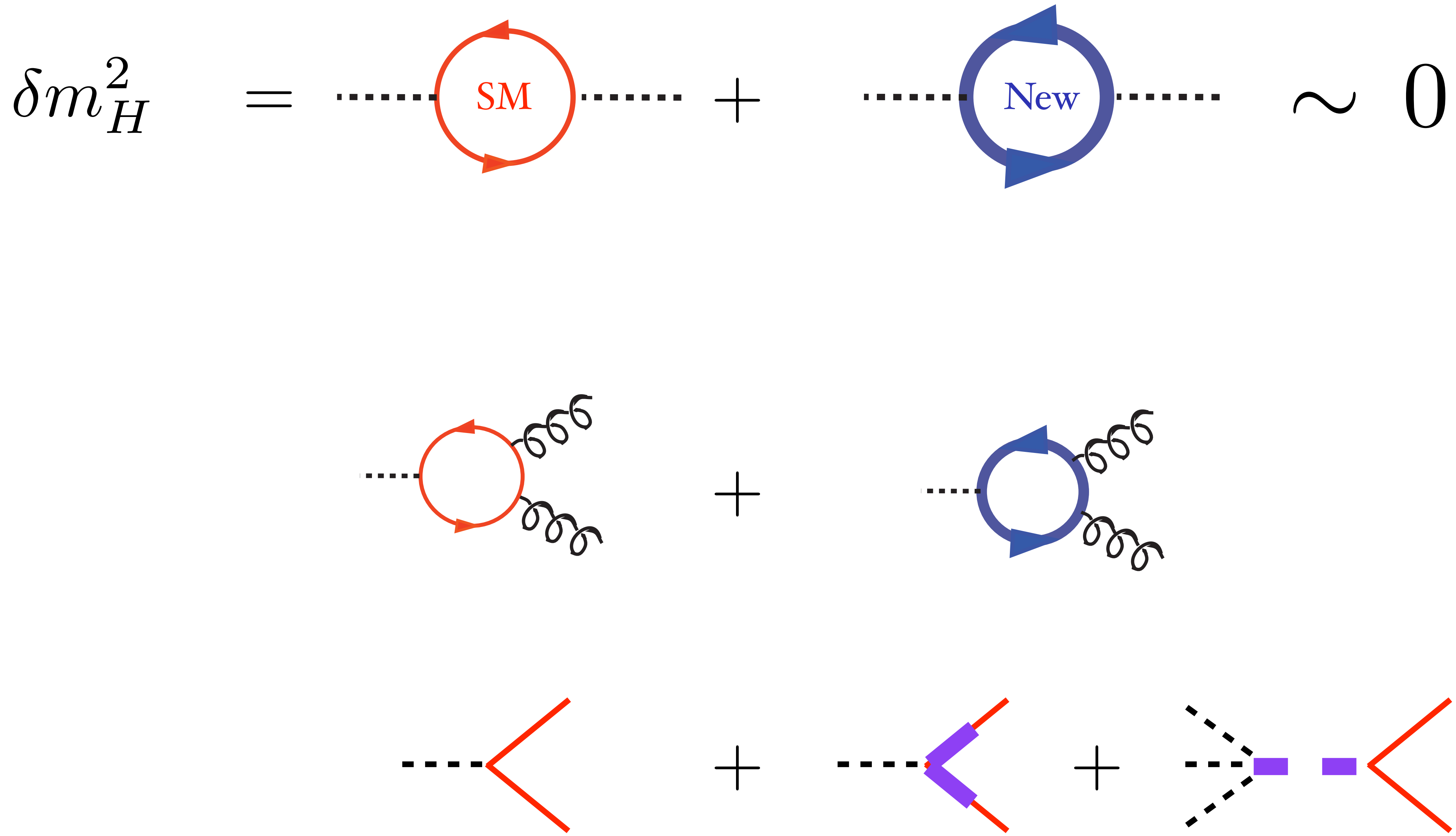
tuning

$\left(\dfrac{125\,\text{GeV}}{\tilde{m}}\right)^2$



The more natural the theory the more the Higgs rates deviate from SM





The more natural the theory the more the Higgs rates deviate from SM

Supersymmetry

- higgs couplings
- EWPT $(\epsilon_1, \epsilon_2, \epsilon_3)$
- $b \to s\gamma$
- ...

$$\frac{\delta\mathcal{O}}{\mathcal{O}_{SM}} \sim \frac{m_{weak}^2}{\tilde{m}^2}$$

soft $\rightarrow$ $O(1)$

super-soft $\rightarrow$ $O(\alpha_t/4\pi)$

Compositeness

$$\frac{\delta\mathcal{O}}{\mathcal{O}_{SM}} \sim \frac{v^2}{f^2}$$

minimal $\rightarrow$ $O(1)$

Little Higgs with T-parity $\rightarrow$ $O(\alpha_t/4\pi)$

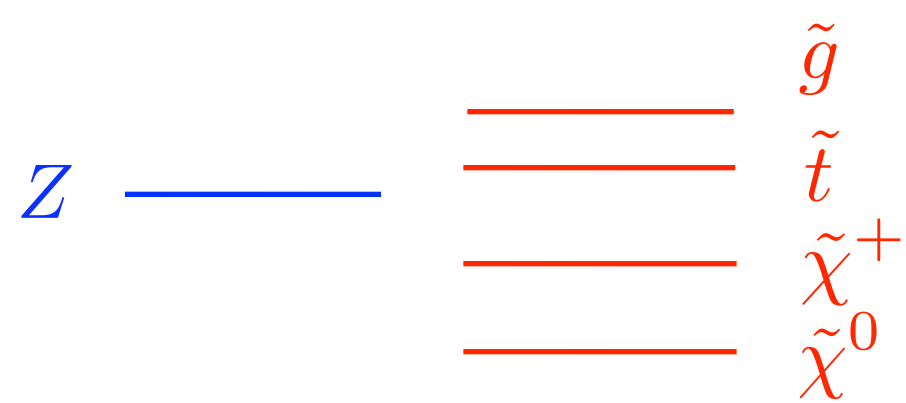
- EWPT $(\epsilon_1, \epsilon_2, \epsilon_3)$
- $b \to s\gamma$
- direct searches (susy)

imply $$\frac{\delta\mathcal{O}}{\mathcal{O}_{SM}} < 1 \qquad (10\%)$$

in most cases do not to expect O(1) deviations in Higgs rates

Perspective on Supersymmetry before and after LHC 7/8

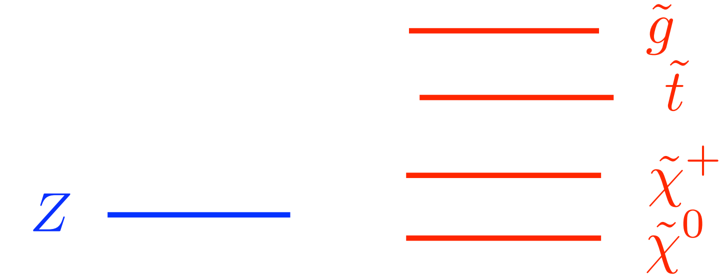
once upon a time, expectation in the less clever models was



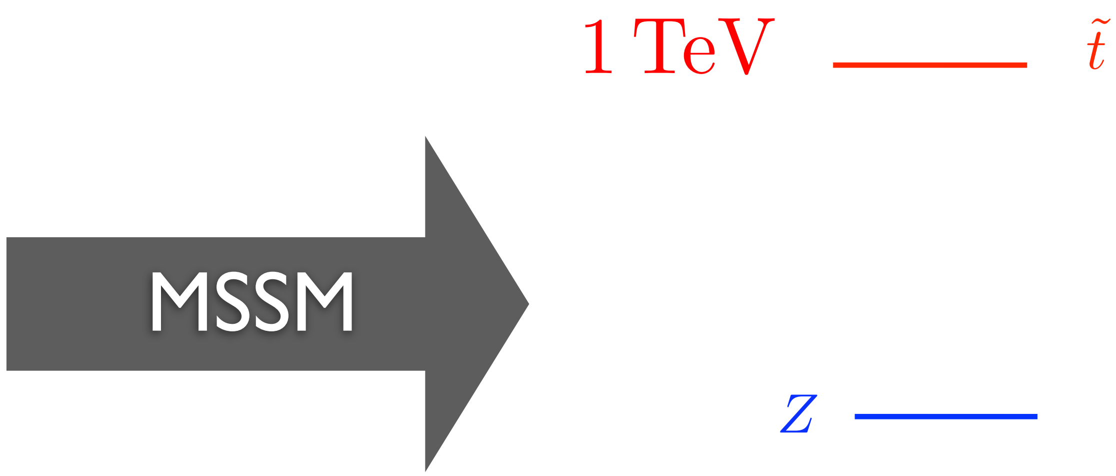
LEP/Tevatron

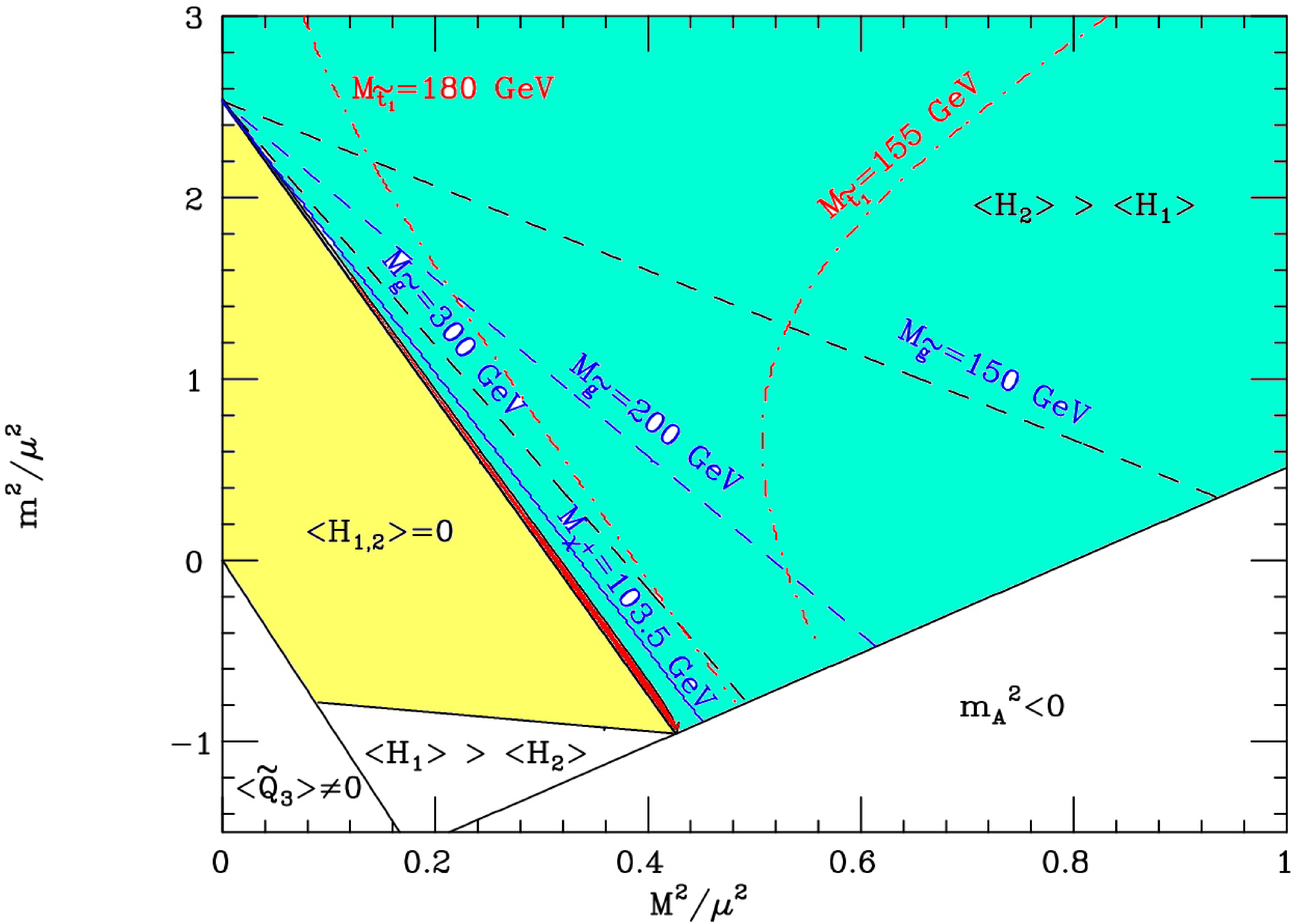
$$m_{\tilde{l}},\, m_{\chi^+} \gtrsim 100\,\mathrm{GeV}$$

$$m_{\tilde{q}},\, m_{\tilde{g}} \gtrsim 300\,\mathrm{GeV}$$



$$m_h > 114.4\,\mathrm{GeV}$$





Giudice, Rattazzi '06

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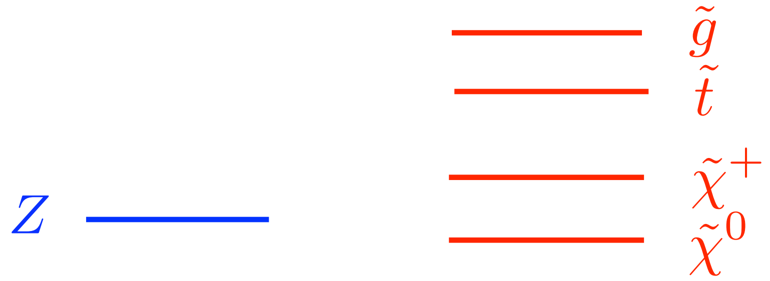

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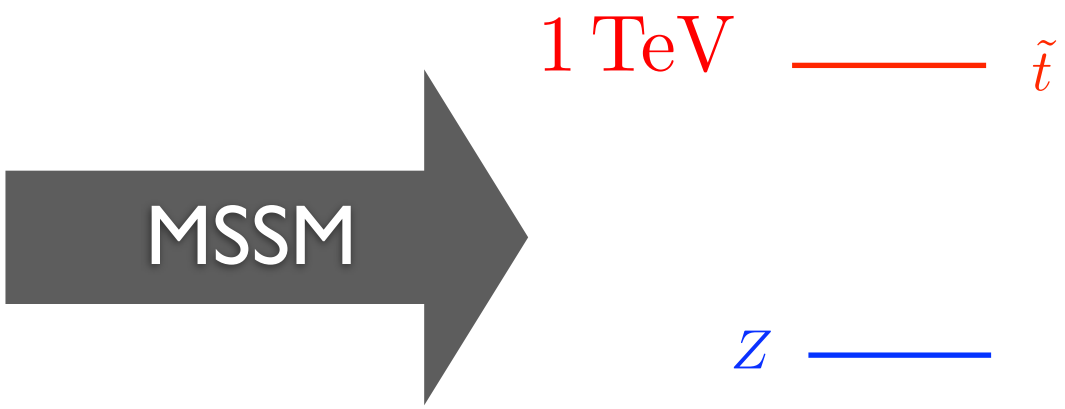

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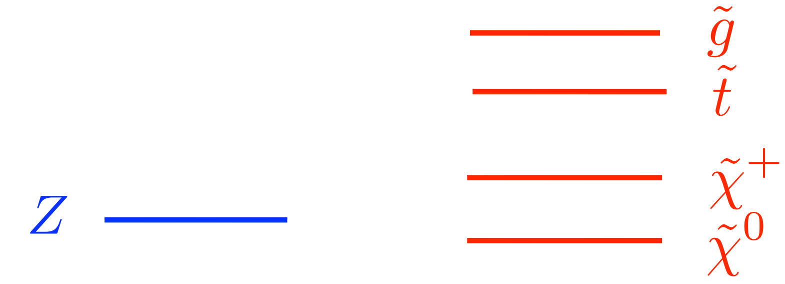

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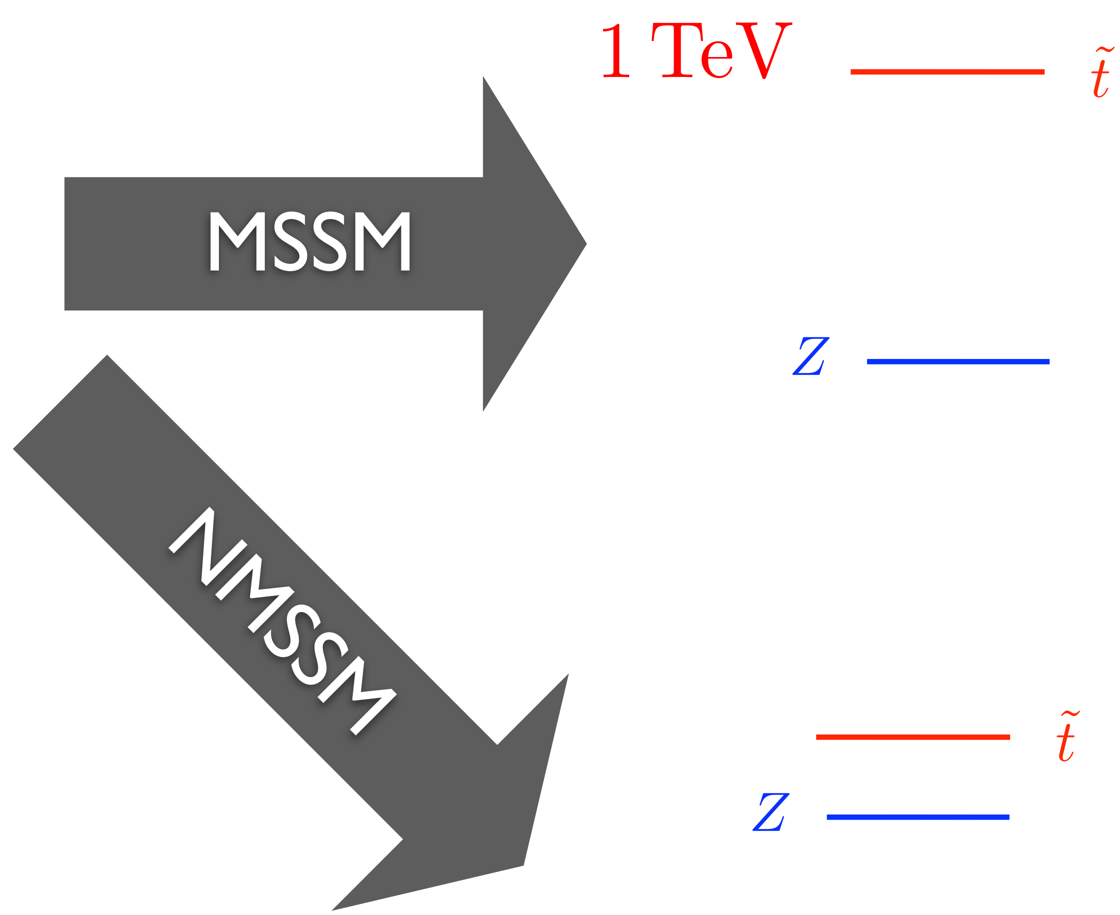


$\lambda S H_1 H_2$

perturbative till M_{GUT}

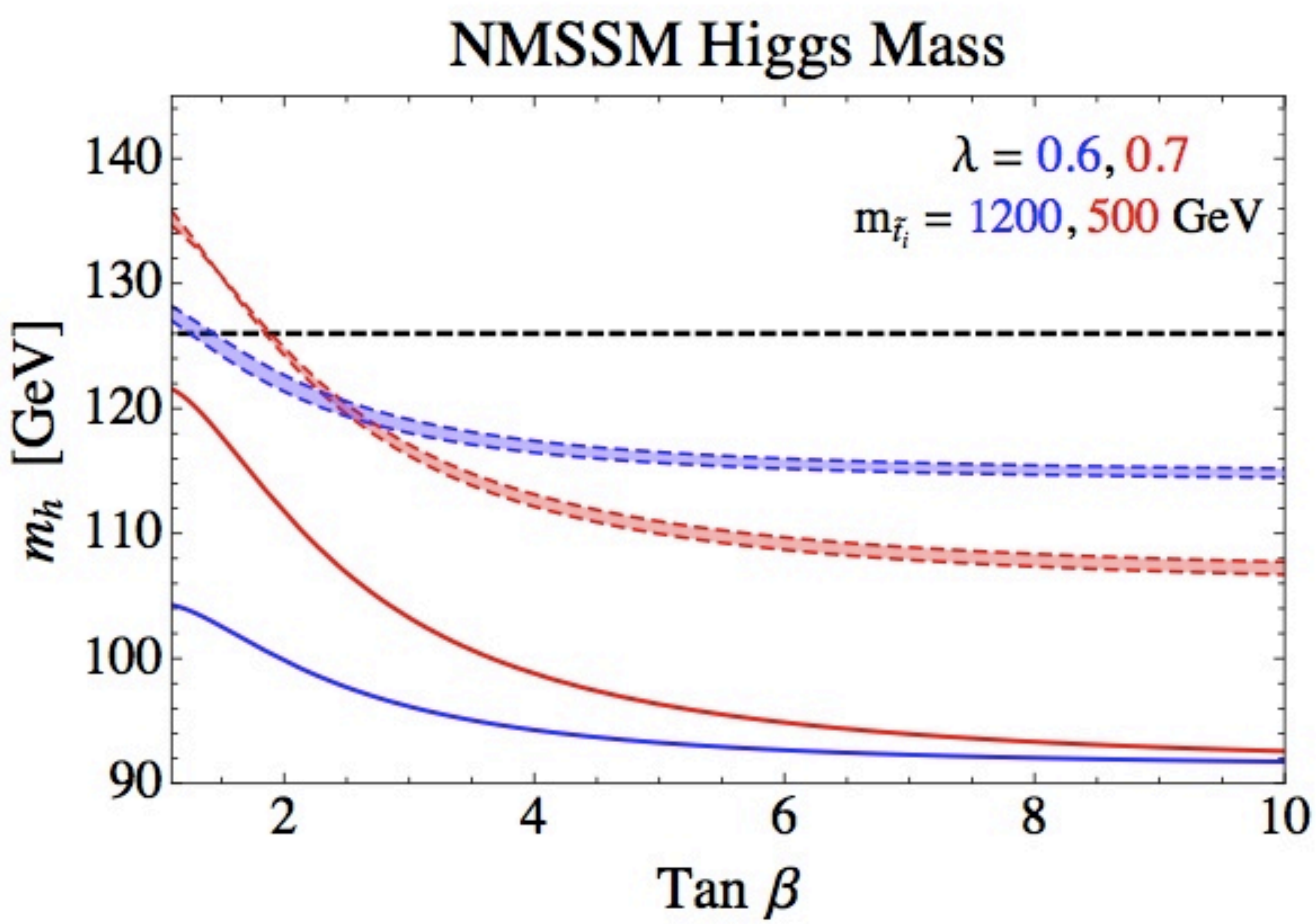
- scenarios with simplest solutions to flavor problems already well constrained back then

  Ex.: gauge mediated models

- radiative EWSB in NMSMM never too good in these simple scenarios

  (but this may not mean too much)

NMSSM after Higgs discovery



Hall, Pinner, Ruderman '11

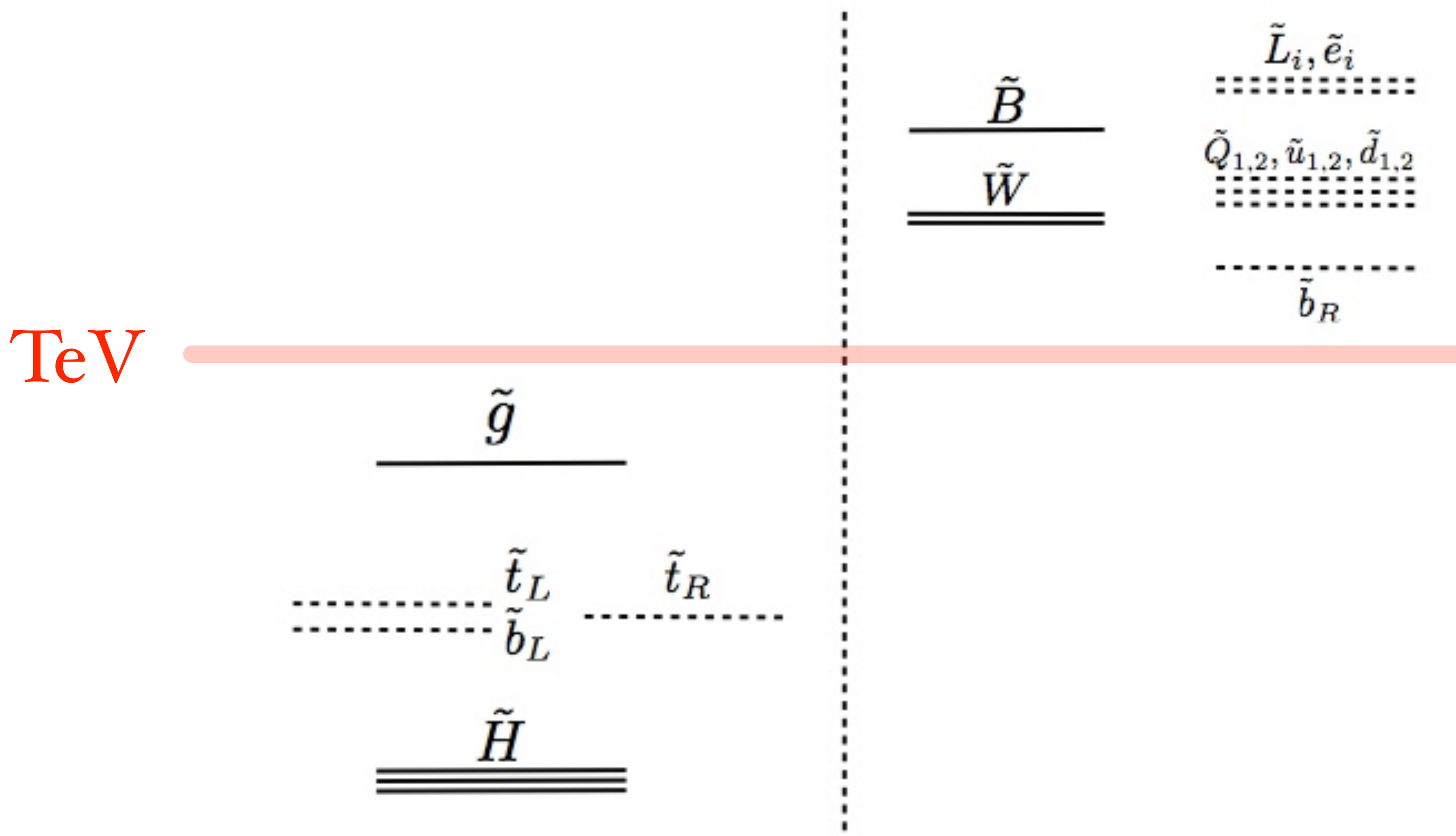
- situation only slightly worse
- GUT perturbativity borderline, but needn't worry too much

see Barbieri et al 2013

The simplest (and perhaps more plausible, but that depends on taste) scenarios were under some pressure already before LHC

LHC has started to put pressure also on the scenarios that stick to naturalness (come una cozza allo scoglio)

not-so-un-Natural SUSY

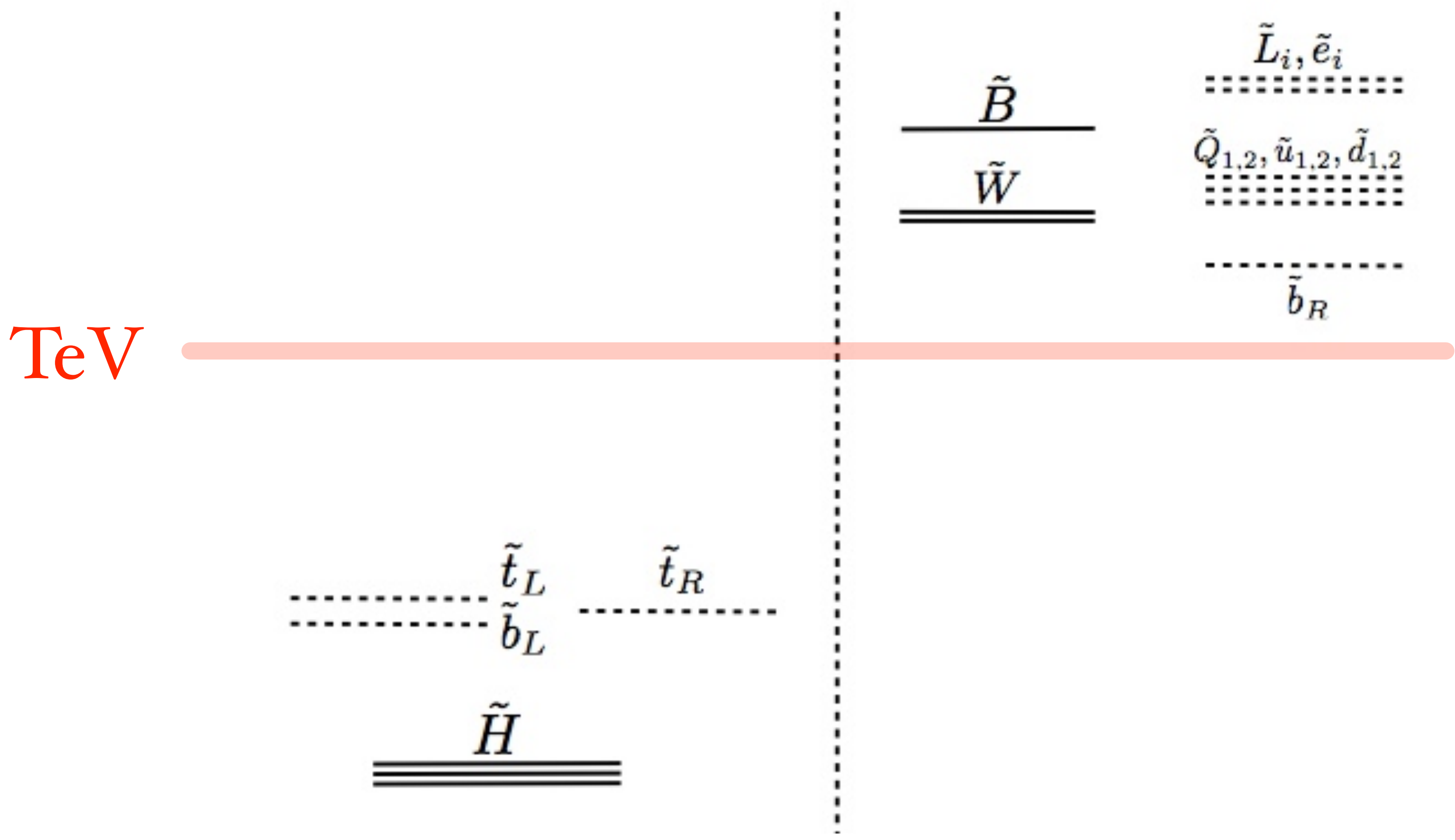


$m_{\tilde{t}} \lesssim 500\,\text{GeV}$ some other physics takes care of m_h

consider all possible ways to suppress the signal:

Dirac gluino, RPV, compressed spectrum,...

not-so-un-Natural SUSY



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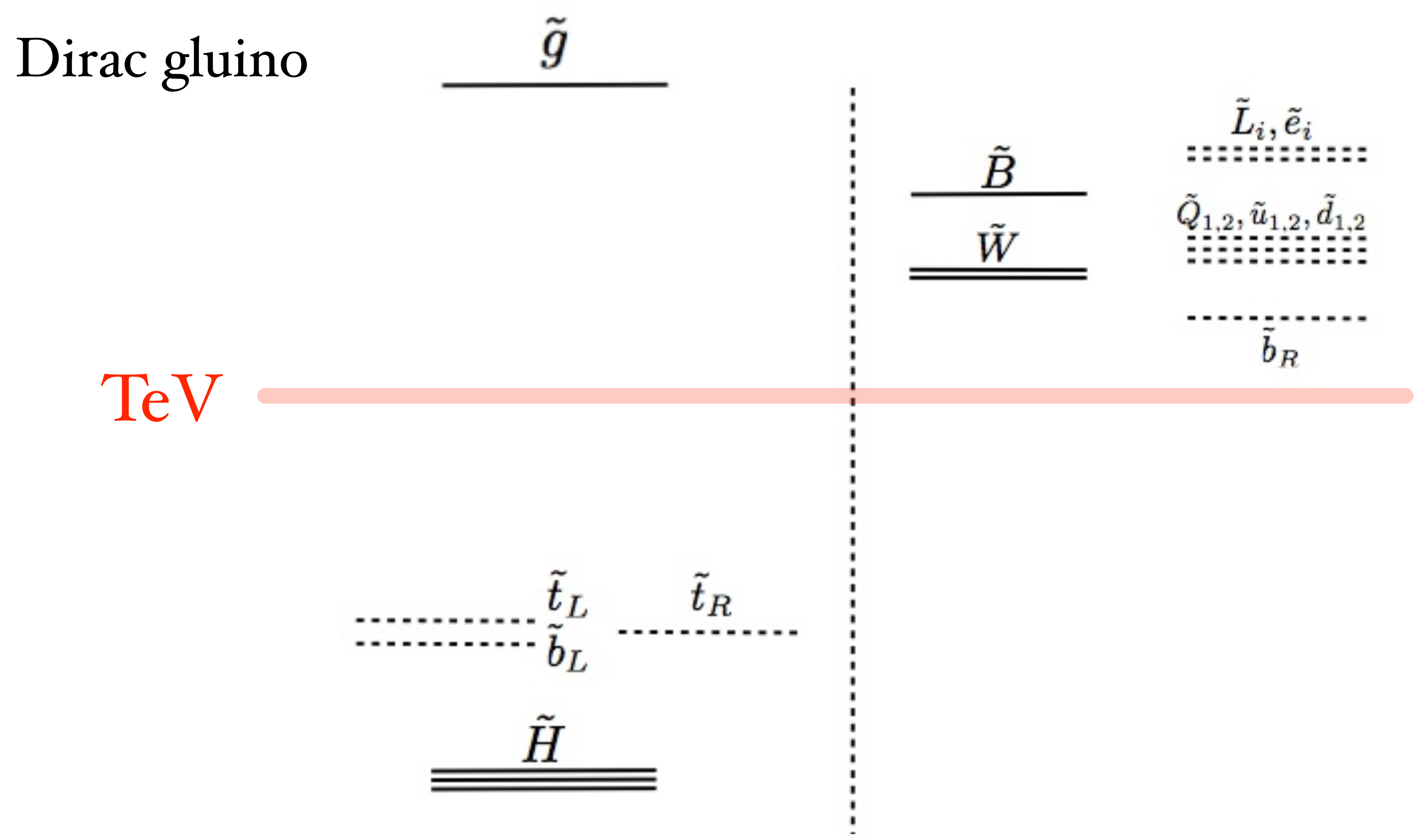

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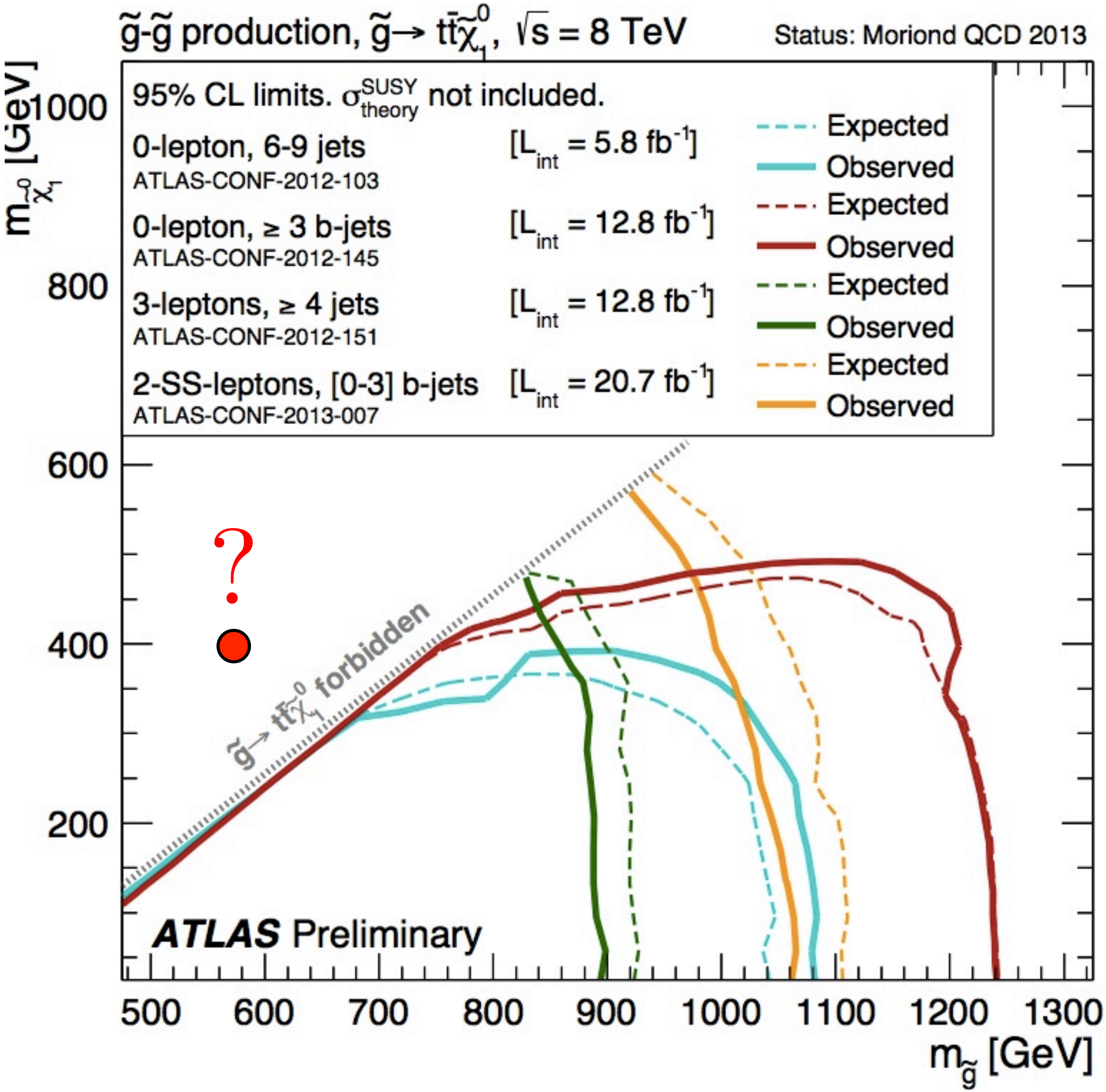
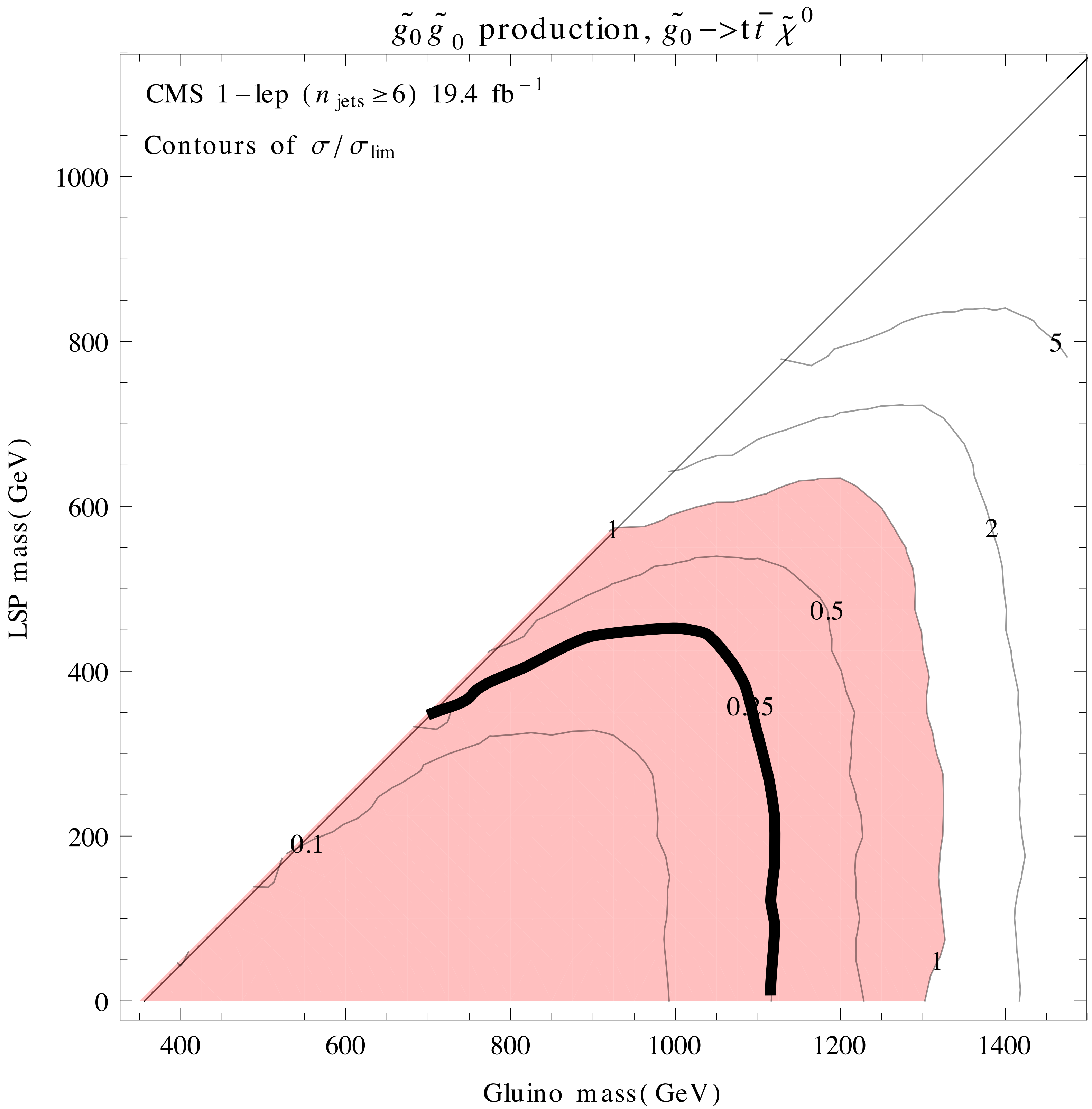

g̃-g̃ production, g̃→ tt̄χ̃⁰₁, √s = 8 TeV
Status: Moriond QCD 2013
95% CL limits. σ^SUSY_theory not included.
0-lepton, 6-9 jets [L_int = 5.8 fb^-1]
ATLAS-CONF-2012-103
0-lepton, ≥ 3 b-jets [L_int = 12.8 fb^-1]
ATLAS-CONF-2012-145
3-leptons, ≥ 4 jets [L_int = 12.8 fb^-1]
ATLAS-CONF-2012-151
2-SS-leptons, [0-3] b-jets [L_int = 20.7 fb^-1]
ATLAS-CONF-2013-007
Expected
Observed
Expected
Observed
Expected
Observed
Expected
Observed
g̃→ tt̄χ̃⁰₁ forbidden
?
ATLAS Preliminary
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
200
400
600
800
1000
500
600
700
800
900
1000
1100
1200
1300

but notice Br(4t) < 0.25 in relevant case

Barbieri, Pappadopulo '09

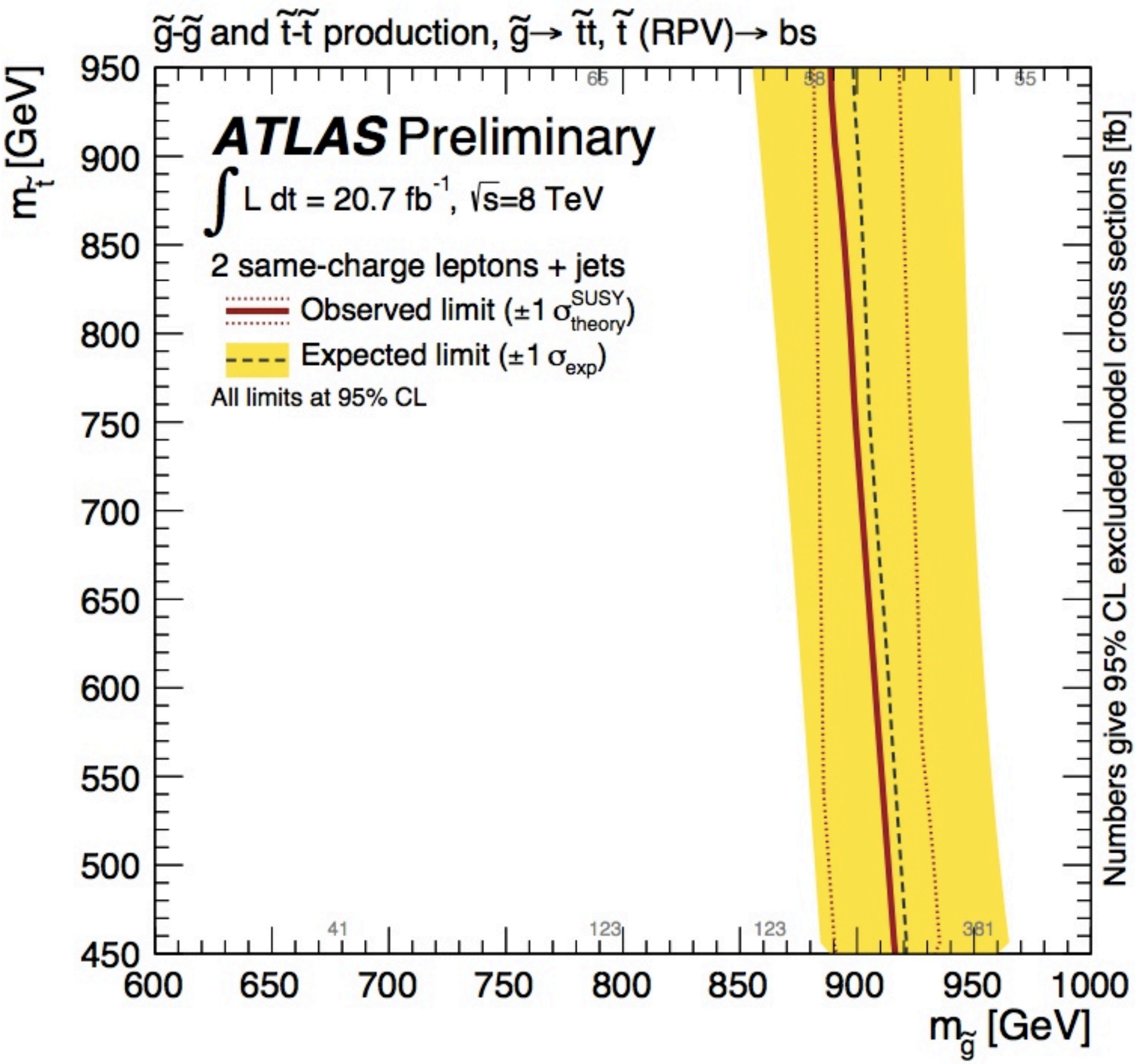


15-20% reduction of bound

Mahbubani '13

still bound very significant in high scale mediation models

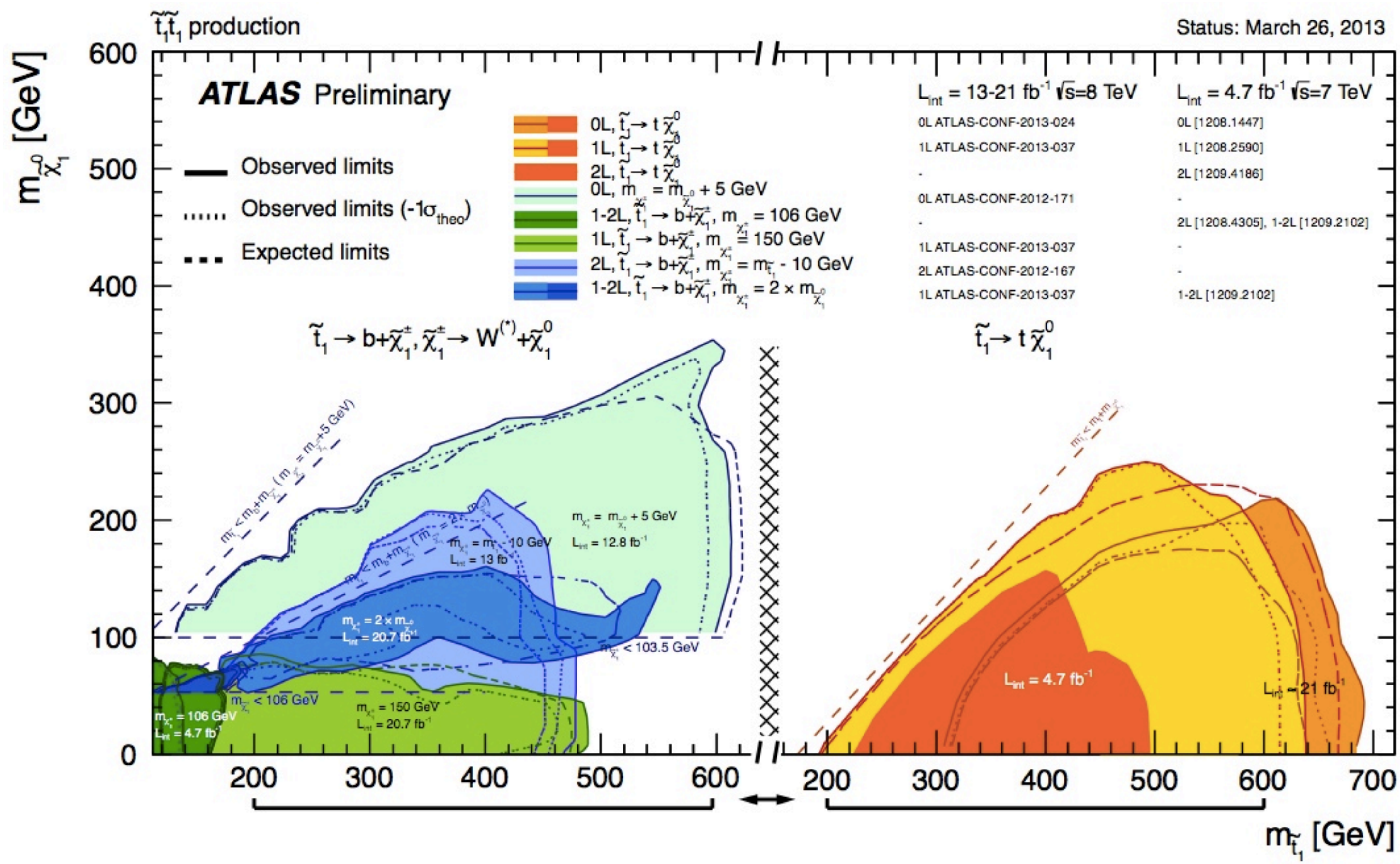
what about a help from baryonic RPV?



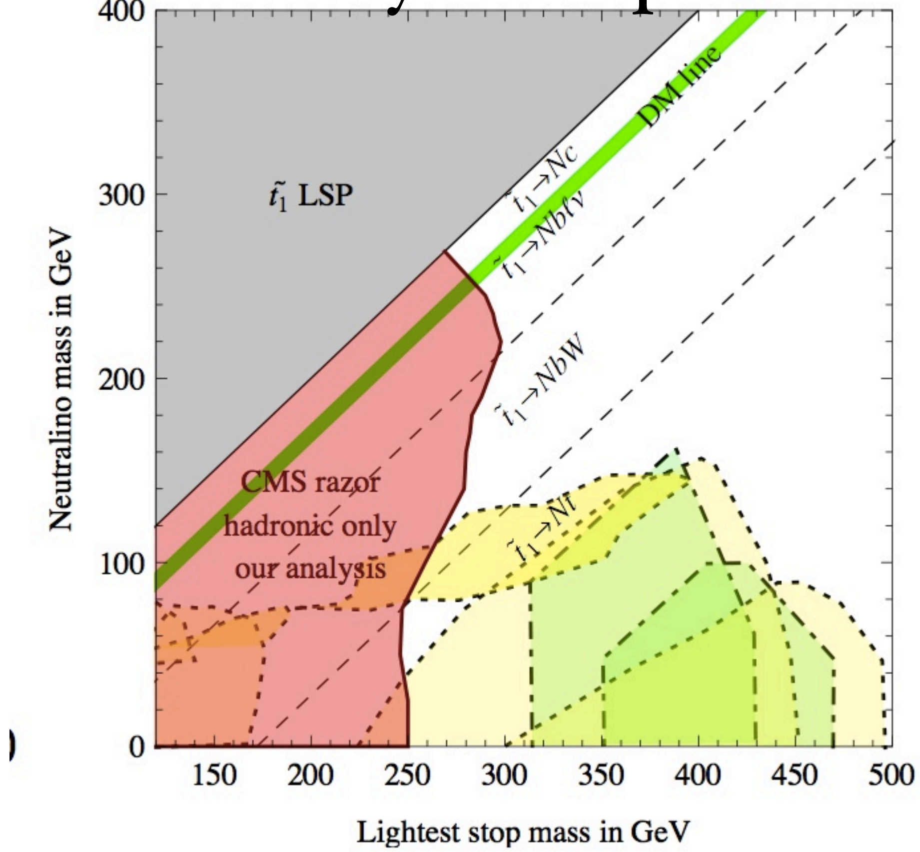
not much help

forget about majorana gluino and go to dirac: supersoft stop masses

zoom on stops and higgsinos

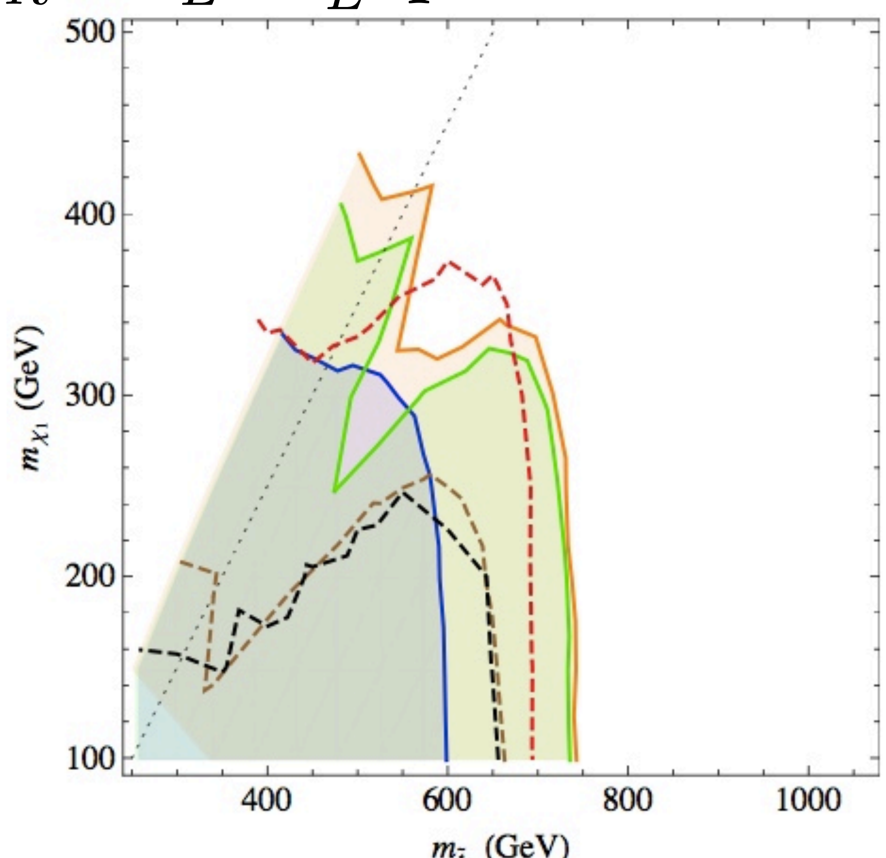


impressive but significant natural regions with squashed spectra remain probably these regions can already be more significantly constrained by different analysis of present data



Delgado, Giudice, Isidori, Pierini, Strumia '13

also addition of $\tilde{t}_R$, $\tilde{t}_L$, $\tilde{b}_L$ production should be considered



Kribs, Martin, Menon '13

what about RPV decaying $\tilde{t}_R$, $\tilde{t}_L$, $\tilde{b}_L$?

$\tilde{g}$

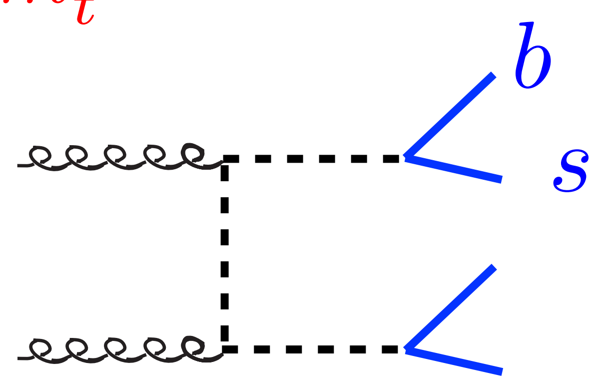
600 GeV

$m_{\tilde{h}} + m_t > m_{\tilde{t}}$

$\tilde{t}$

$\tilde{h}^0_{1,2}\, \tilde{h}^{\pm}$

t



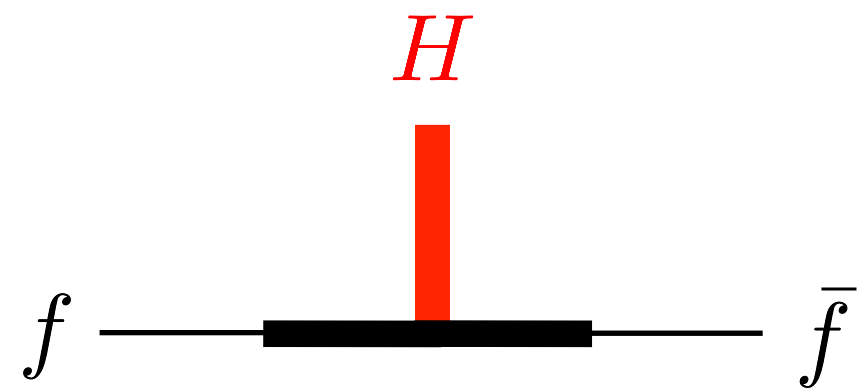
stiamo staccando le cozze dallo scoglio, ma ce n’é ancora

looking forward to next run and to even more clever analyses

é ancora presto per un mondo senza cozze (eg. mini-split)

Compositeness

Flavor: only option partial compositeness

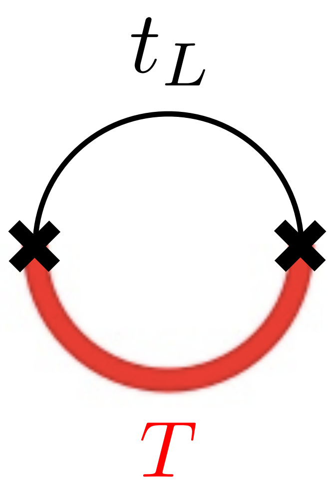


without any additional symmetry

FCNC	$m_* \gtrsim 10-20\,\mathrm{TeV}$
edms	$m_* \gtrsim 40\,\mathrm{TeV}$
$\mu \to e\gamma$	$m_* \gtrsim 150\,\mathrm{TeV}$

with combination of SU(2)'s and SU(3) can bring scale down to ~TeV

$V(H) =$



top ⟷ partners $(B_{-1/3}, \quad T_{2/3}, \quad X_{5/3}, \quad \Xi_{8/3}, \ldots)$

expectations from naturalness

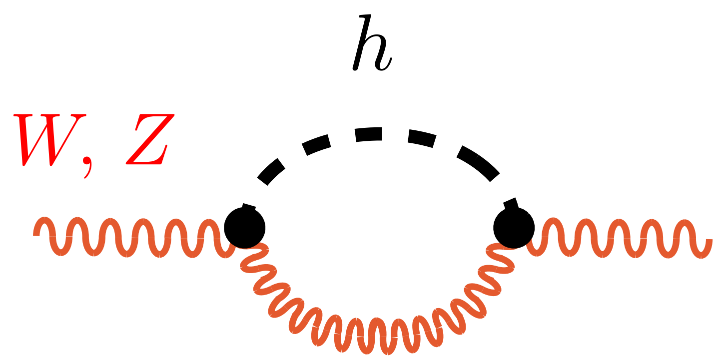
generic $\quad V \equiv V(H/f)$

$$\frac{v^2}{f^2} = O(1)$$

$m_h \simeq 125\,\mathrm{GeV}$

$$\left(\frac{400\,\mathrm{GeV}}{m_T}\right)^2 = O(1)$$

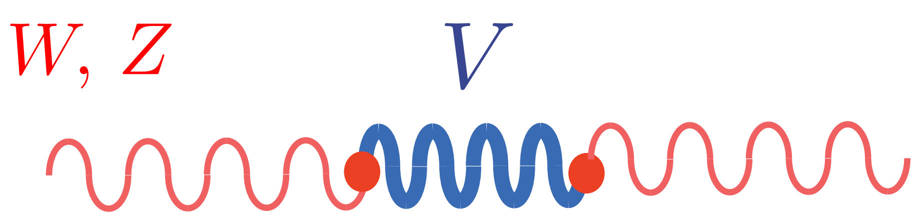
Electroweak Precision Tests



$\Delta\widehat{S},\ \Delta\widehat{T}$

$$\frac{v^2}{f^2} \lesssim 0.05 \qquad (0.2)$$

pessimist   optimist



$$\Delta\widehat{S} \sim \frac{m_W^2}{m_V^2}$$

$$m_V^2 \gtrsim 2 - 3\,\text{TeV}$$

Tension between naturalness and EWPT

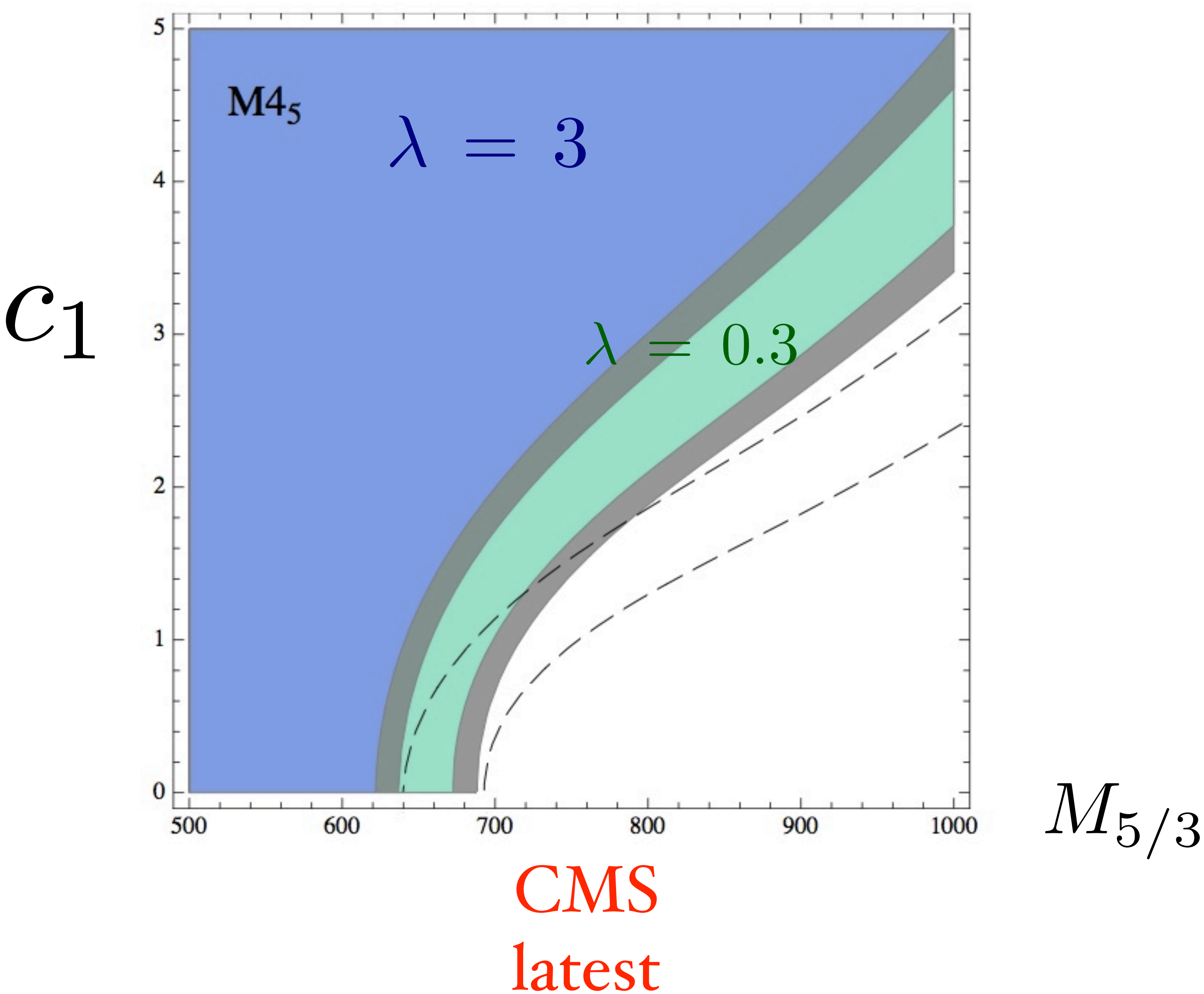
Technical naturalness demands structural complexity $\left(m_V \gg m_T \right)$

Higgs couplings

$$\frac{\delta g}{g_{SM}} \sim \frac{v^2}{f^2} \lesssim 0.2$$ from EWPT

wait for more integrated luminosity to break new grounds

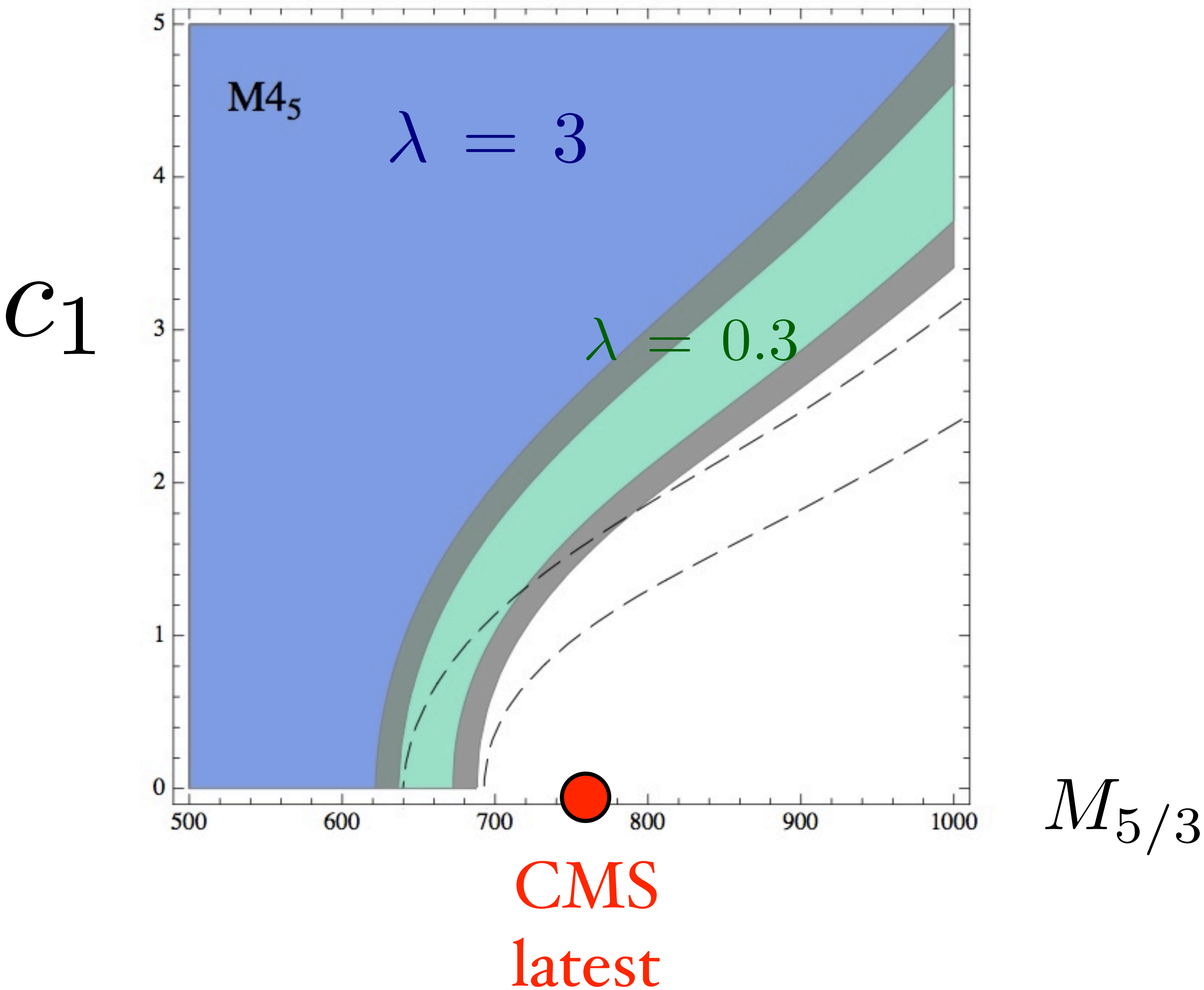
De Simone, Matsedonkyi, Rattazzi , Wulzer ’12



$$\xi \equiv \frac{v^2}{f^2} = 0.2$$

this is a very significant direct ‘test’ of naturalness

De Simone, Matsedonkyi, Rattazzi , Wulzer '12



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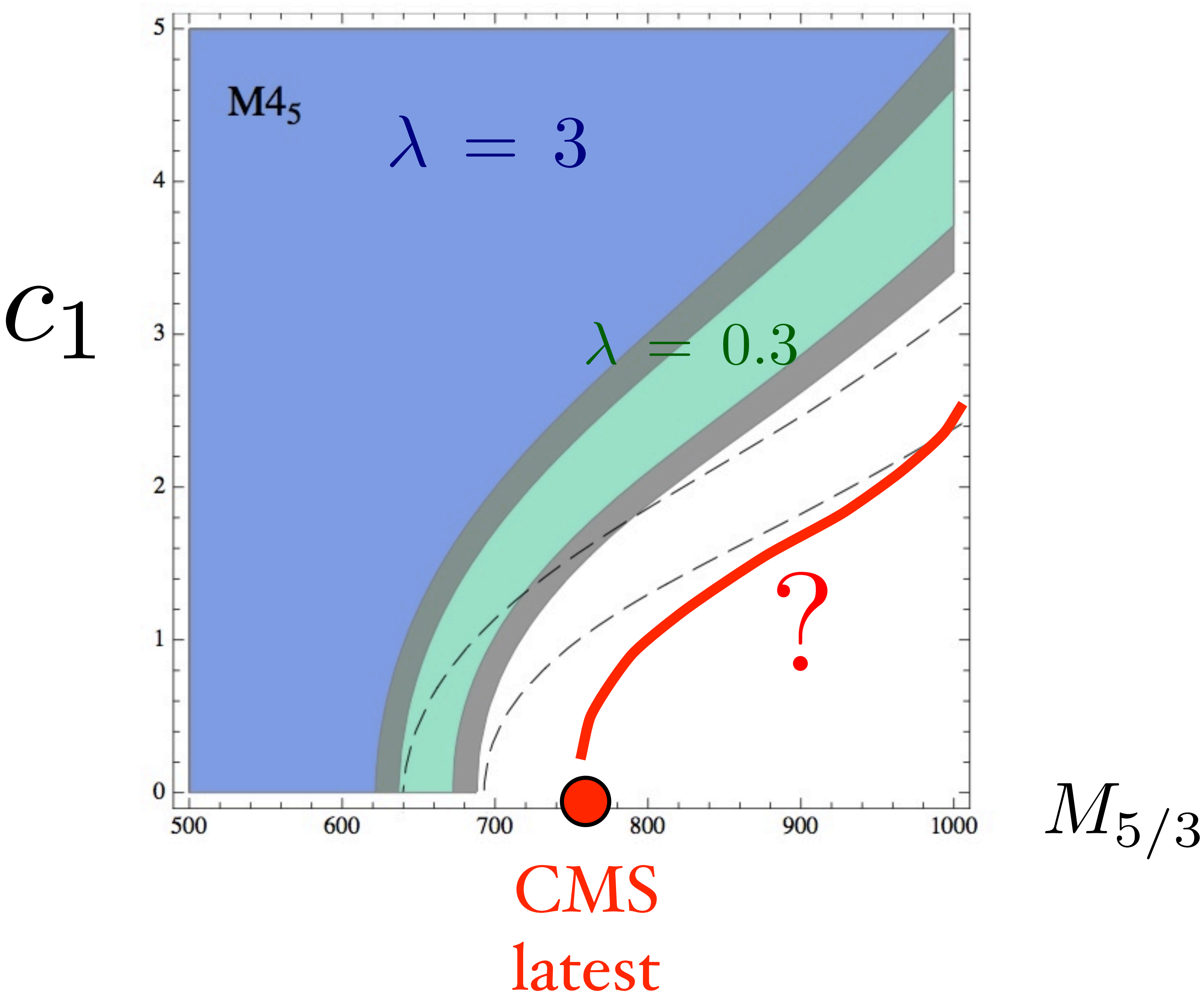
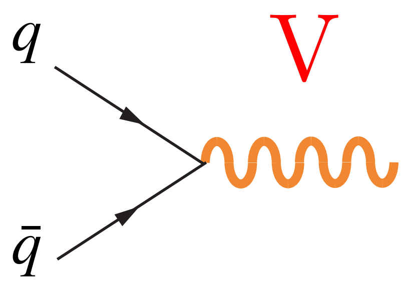


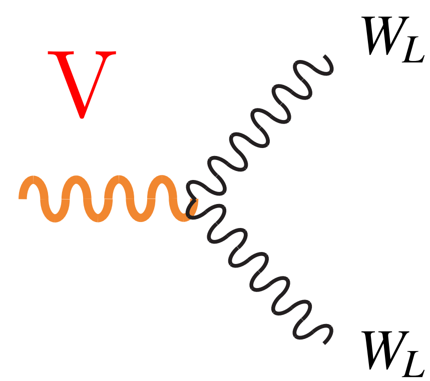
$$\xi \equiv \frac{v^2}{f^2} = 0.2$$

this is a very significant direct 'test' of naturalness

Vector Resonances



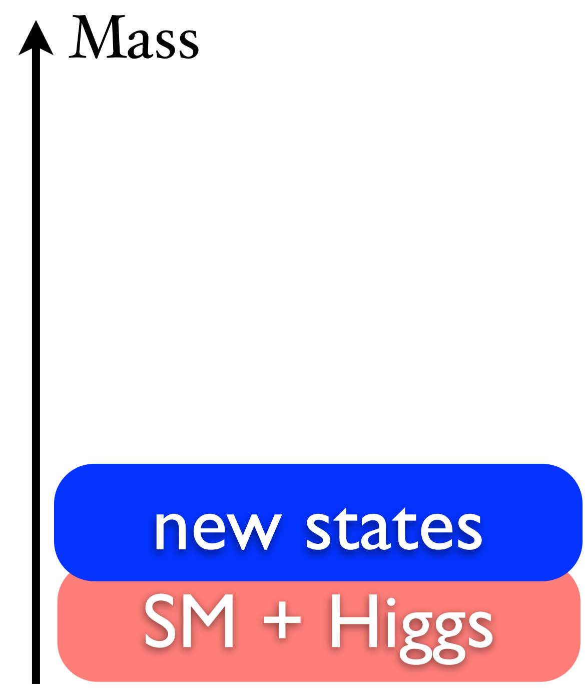
$$= \frac{g_W^2}{g_V} \ll g_W$$



$$= g_V$$

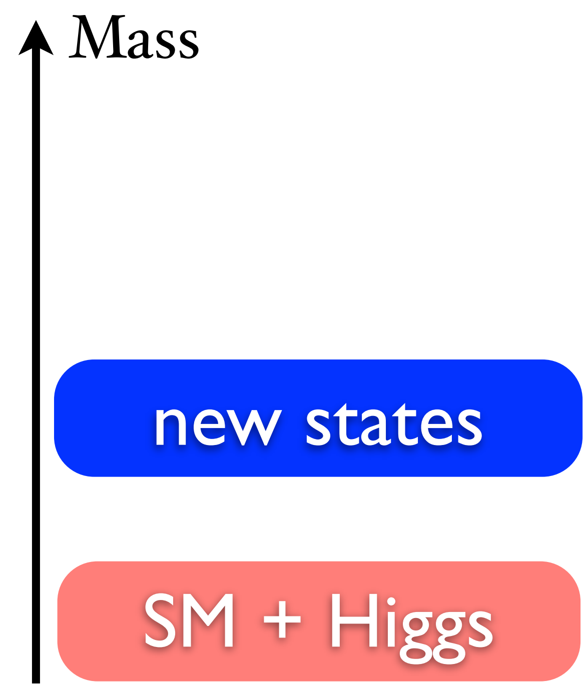
- resonances couple ‘superweakly’ to light fermions
- significantly different from weakly coupled W’ and Z’
- present bound just around TeV signicantly below EWPT bound
- wait for LHC13 to step into interesting region

Higgzoologia



Can use effective lagrangian to describe deviations from SM

= simple parametrization encompassing a large class of models



Can use effective lagrangian to describe deviations from SM

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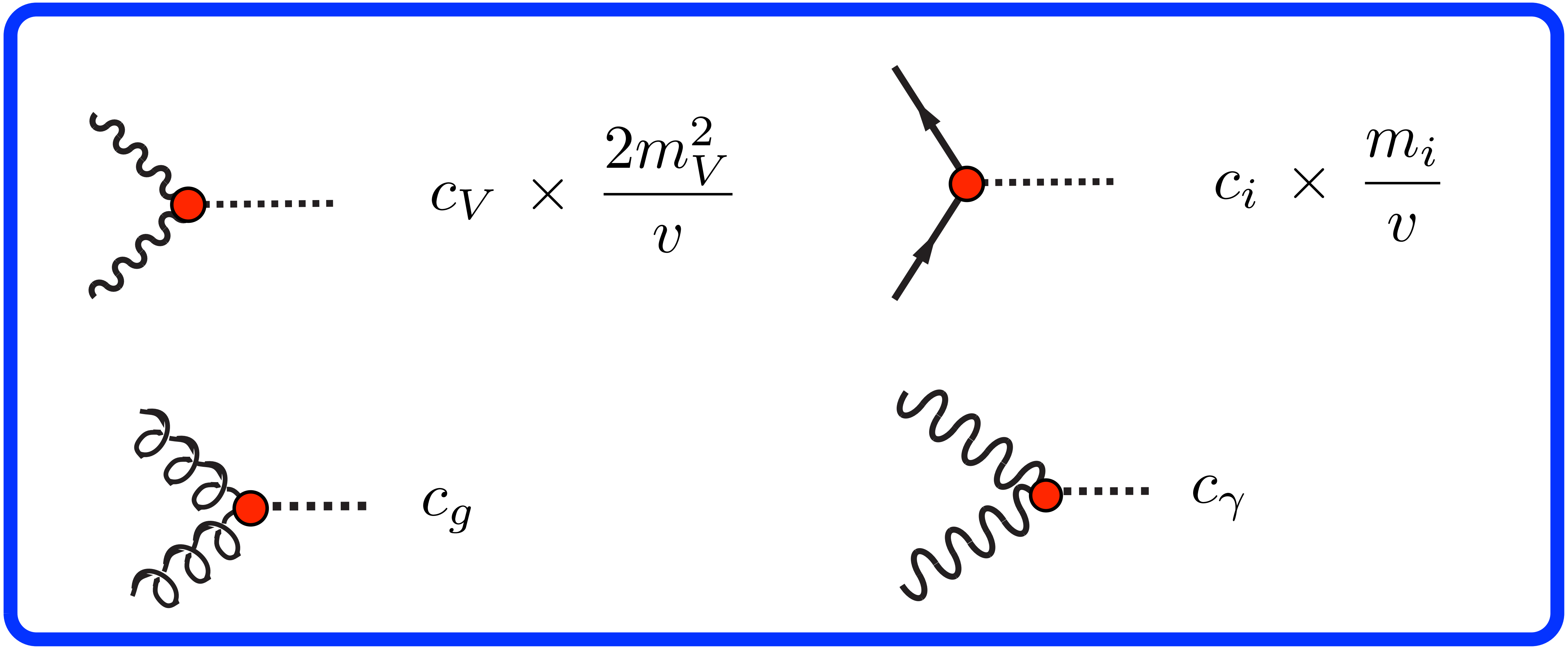
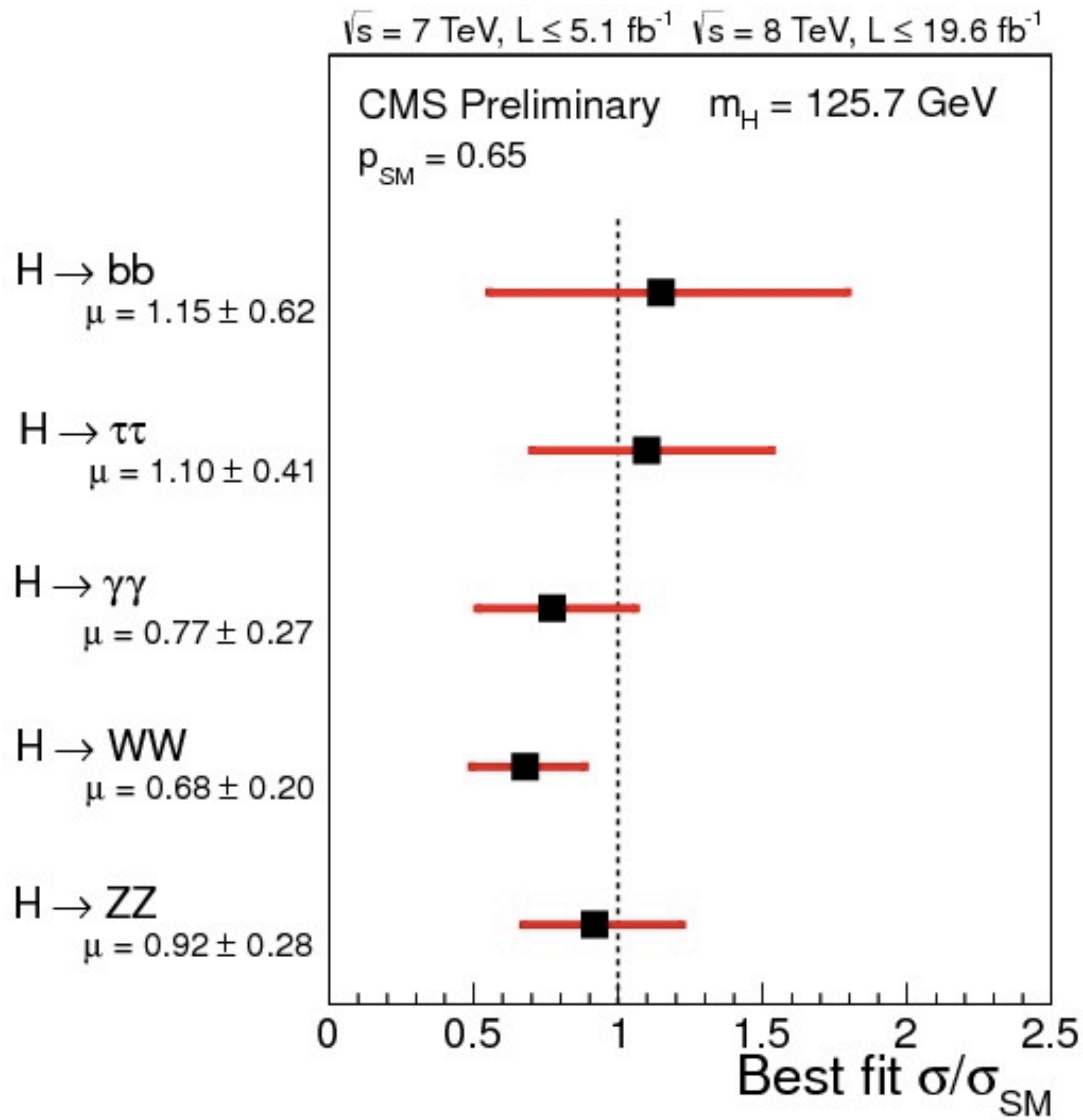


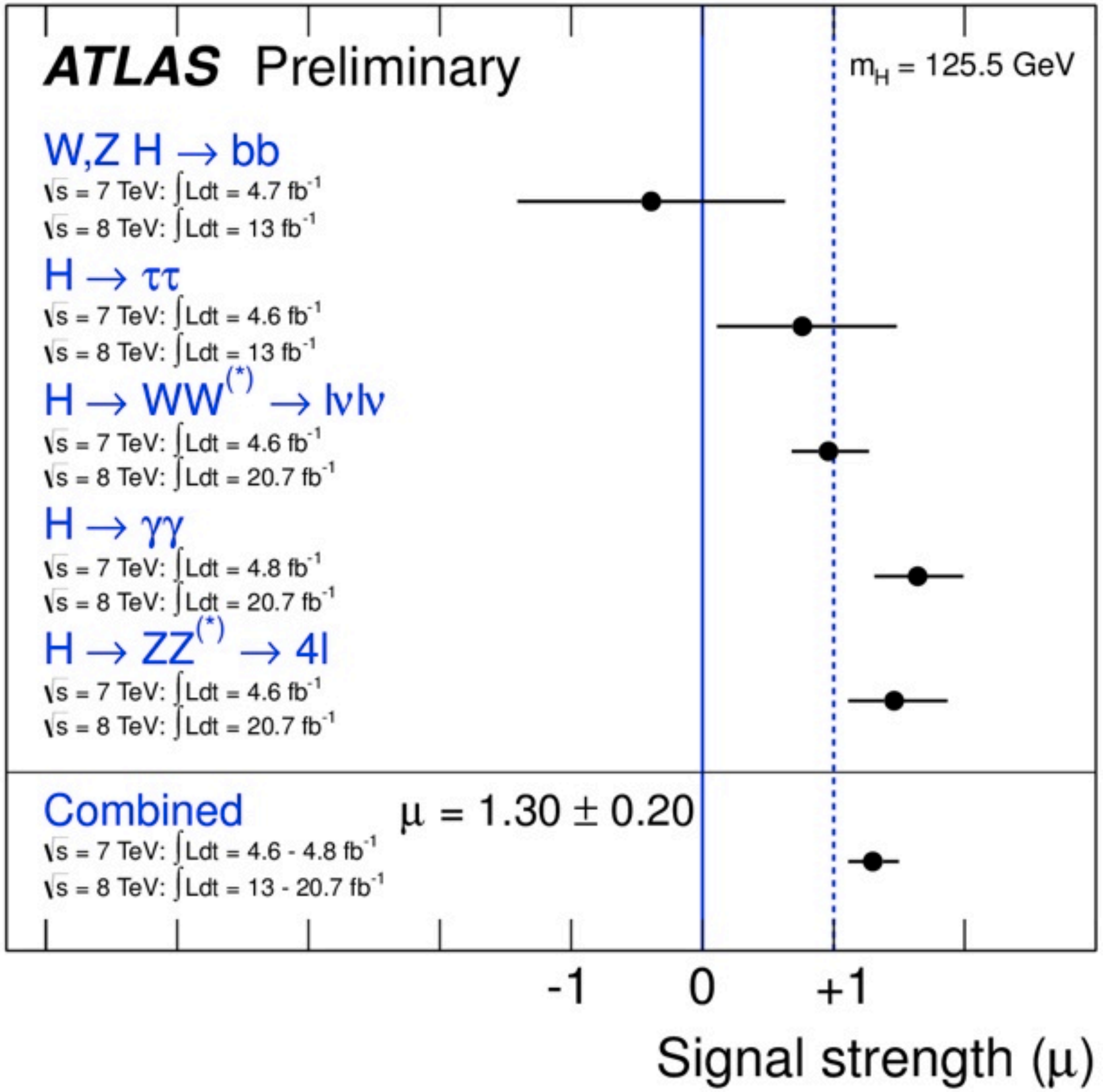
$c_V > 1$ ⟷ only if ∃ scalar of electric charge 2

$c_b > 1,\ c_t < 1$ ⟷ MSSM

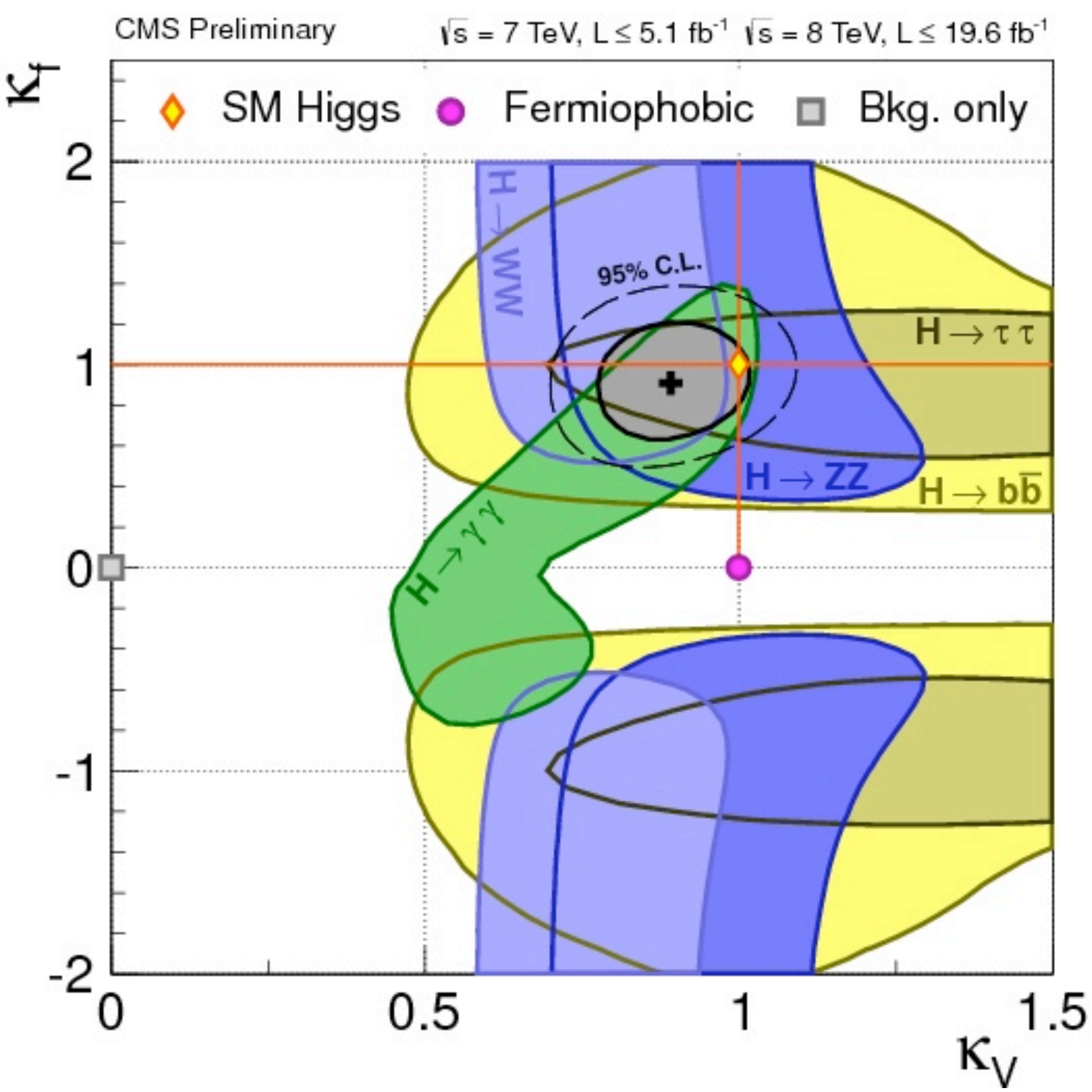
$c_b < 1,\ c_t > 1$ ⟷ NMSSM dominated quartic

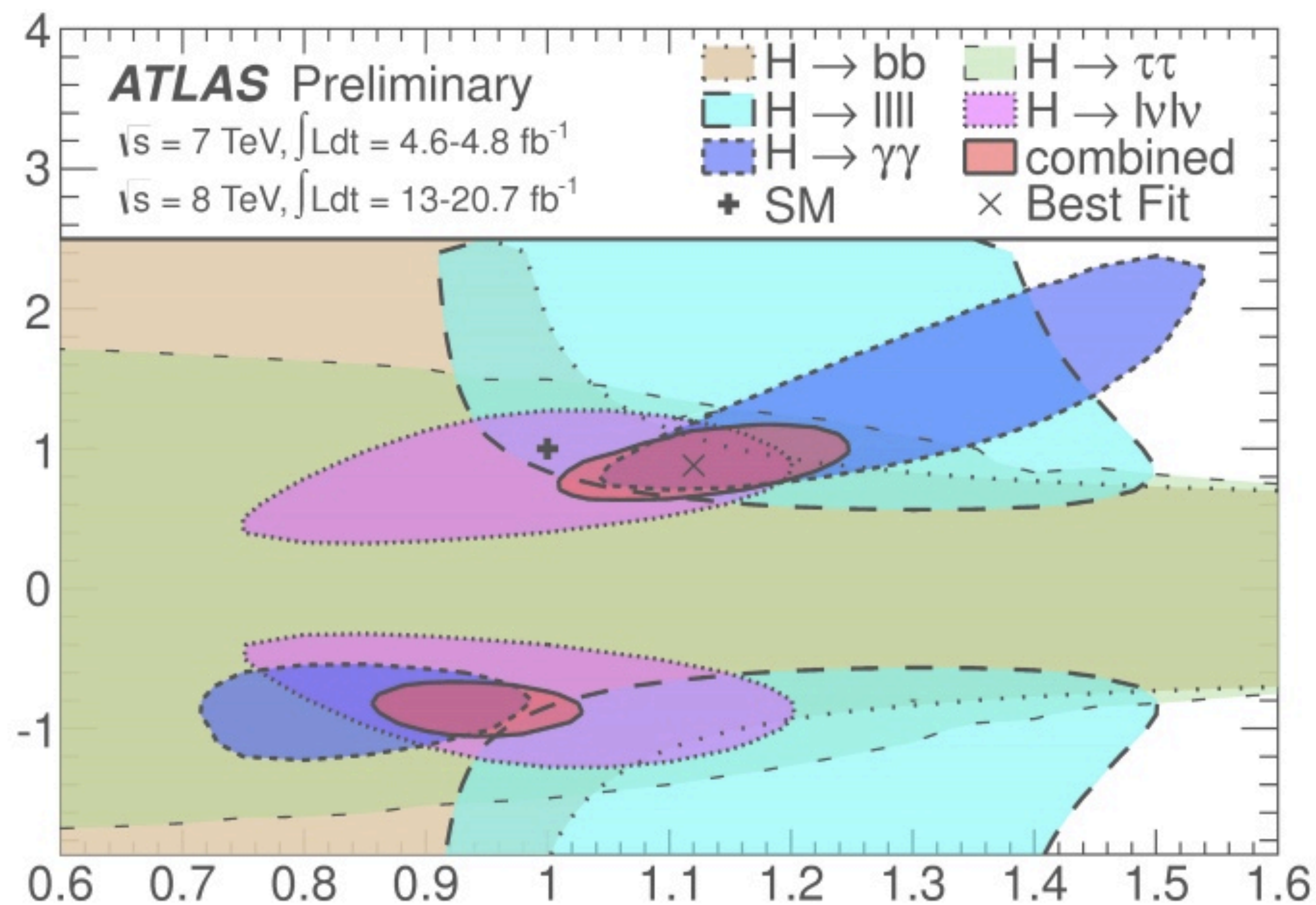
$c_V\,, c_f < 1$ $\quad c_g\,, c_\gamma \sim 0$ ⟷ Composite Higgs





No clear trend of deviation from SM


CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
SM Higgs
Fermiophobic
Bkg. only
95% C.L.
H → WW
H → ττ
H → ZZ
H → bb̄
H → γγ
κf
κV
2
1
0
-1
-2
0
0.5
1
1.5

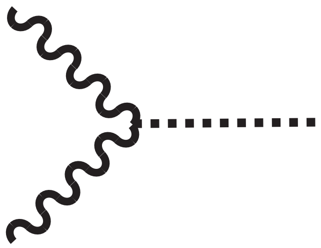

ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV, ∫Ldt = 13-20.7 fb-1
H → bb
H → llll
H → γγ
SM
H → ττ
H → lνlν
combined
× Best Fit
4
3
2
1
0
-1
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6


Higgs comin' !!

Welcome Higgs !!

The precision frontier

single Higgs physics

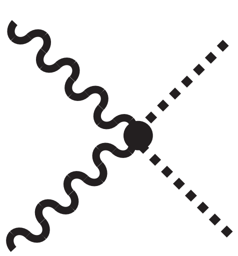


measures $\frac{g_{NP}^2 v^2}{M_{NP}^2} \lesssim$ fine tuning

EWPT	HL-LHC	ILC-LEPpone
10%	5%	1%

precision Higgs physics breaks ground in the test of naturalness
though it can only give us indirect clues

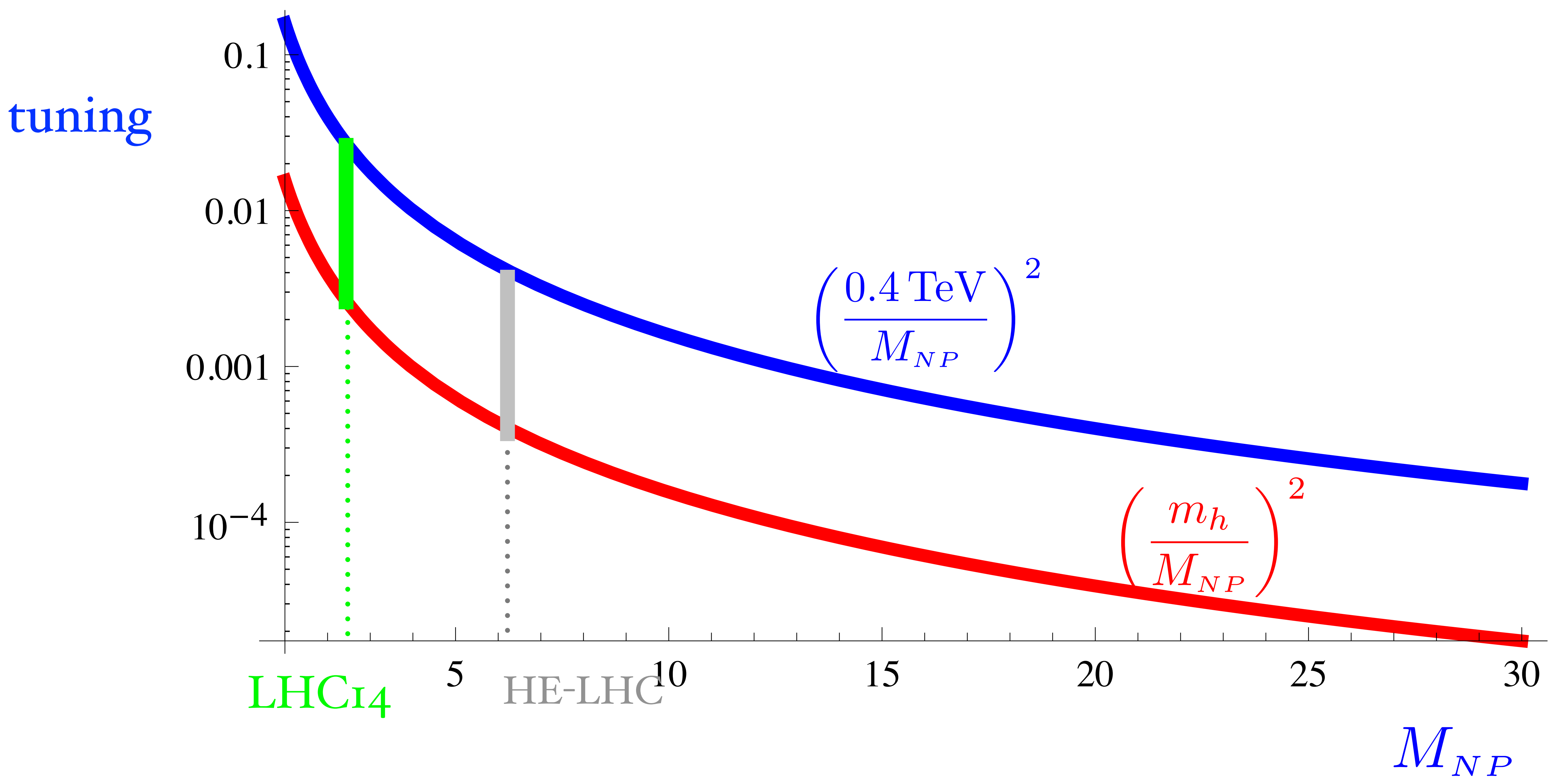
semidirect clues



at CLIC

sensitive to tuning of ~1%

The energy frontier



Summary

- discovery of Higgs boson with rates in agreement with SM within the present precision of 30% is far from unexpected: it is basically a corollary of results of LEP/Tevatron/B-factories

- direct searches are directly pushing several scenarios (especially in SUSY) into 1% tuning grounds, though that is basically were the simplest (and maybe nicest) models were already expected by indirect reasoning (ex, MSSM with flavor universal soft terms)

- LHC searches are now also putting significant pressure on cleverly natural models, though regions with moderate tuning are not ruled out yet

- LHC13 will break grounds on those regions and perform a comprehensive test of naturalness

- HL-LHC will break grounds in EW physics by testing Higgs rates at, so they say, 5%